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Space-Based Observations of Satellites from the MOST Microsatellite

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R.L. Scott, B. Wallace, D. Bedard

The tracking data herein is based on data from the MOST satellite, a Canadian Space Agency mission, jointly operated by Dynacon Inc., the University of Toronto Institute for Aerospace Studies and the University of British Columbia, with the assistance of the University of Vienna.

Defence R&D Canada – Ottawa

Technical Memorandum

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Abstract

On October 12th 2005, Canada's MOST spacecraft acquired Canada's first microsatellite-based observations of a deep space satellite. MOST repeated this success by conducting an observation on a different spacecraft the following day. This report summarizes the experimental setup, access particulars, metric and photometry data. Comparison of the derived orbital metric data with high precision ephemerides yielded root mean square errors of 13 arcseconds. The errors are shown to result largely from timing uncertainties inherent in the MOST spacecraft. The space-based photometric measurements of these spacecraft were consistent with ground based observations. Analysis of these results indicates that microsatellite platforms show technical promise as a low cost means to conduct space surveillance from an orbiting platform.

Résumé

Le 12 octobre 2005, le microsatellite MOST du Canada a acquis les premières images canadiennes d'un satellite évoluant dans l'espace lointain et il a réédité son exploit dès le lendemain en observant un autre engin spatial. Le présent rapport présente sommairement la configuration expérimentale du satellite, les modalités d'accès ainsi que les données métriques et de photométrie. La mise en relation d'éphémérides très précises et des données métriques orbitales dérivées a donné lieu à des erreurs-types de 13 secondes d'arc. Ces erreurs semblent en grande partie attribuables aux incertitudes liées à la synchronisation, lesquelles sont inhérentes au microsatellite MOST. Les mesures photométriques des engins spatiaux prises depuis l'espace correspondent aux observations faites depuis le sol. Suite à l'analyse des résultats, les microsatellites s'annoncent prometteurs sur le plan technique et pourraient constituer une solution économique pour la surveillance spatiale depuis des plateformes orbitales.

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Executive summary

On 12 October 2005, the MOST microsatellite marked a milestone in Canadian Surveillance of Space (SofSP) efforts by conducting the first Canadian led space-based observations of an Earth orbiting object. Tracks of two different Global Positioning Satellites were taken using the optical telescope aboard the MOST microsatellite.

MOST is a Canadian Space Agency (CSA) microsatellite designed to conduct high-accuracy photometric observations of bright-stars and is the first microsatellite to feature a very high stability (3 arcsecond) attitude control system (ACS). Both DND and Defence R&D Canada are investing in space-based SofSP platforms (SAPPHIRE and NEOSSat) and both are considering the use of technology and components used on the MOST spacecraft. As a risk reduction measure for the HEOSS TDP, a test was authorized by the Canadian Space Agency to use MOST to attempt detection of deep space satellites in support of these DND and DRDC projects.

MOST observed the satellite GPS IIR-11 (SSN# 28190) at a range of 23,000 kilometres. This was the first, tasked, space-based observation of another spacecraft using a microsatellite. On the following day, MOST repeated the success by taking an observation of GPS IIR-04 (SSN #26360). Both images were of good quality and both stars and the satellite streaks were plainly discernable in the images.

Orbital position measurements of the targeted satellites were determined to have 13 arcseconds RMS accuracy. This is outside of the performance objectives of the NEOSSat and Sapphire programs but is nonetheless excellent as MOST was not designed to image, let alone conduct satellite tracking. The largest portion of this uncertainty is argued to be due to timing uncertainty on-board MOST. The spacecraft operator estimated the clock uncertainty aboard MOST to be 100 milliseconds; analysis of the results suggest this timing error may be closer to 300 milliseconds and is likely due to an unmodelled systematic effect in the image acquisition process.

The observed GPS satellites were favourably illuminated, and MOST measured their astronomical magnitudes to be 12.1±0.2 and 11.5±0.1. This is a MOST-specific magnitude which is red sensitive. The background sky brightness was also determined and was found to be 18.2 magnitudes/arcsec^2. This bright background is possibly due to a light leak onboard MOST or to scattered Earthshine. Both of these factors require consideration during observation of satellites as extraneous Sun/Earthshine result in detector noise levels that could overwhelm the target satellite signal.

This test illustrates that the MOST instrument and ACS show technical promise as a space surveillance system. While the MOST ACS can provide arcsecond level *stability,* the *agility* of the ACS needed to fulfill NEOSSAT’s mission has not been qualified. Future testing, if authorized, should attempt a limited test of ACS agility, where the observing spacecraft would slew from one satellite to another in succession, achieving fine pointing lock at each interval.

Scott, R.L.2006. *Space-Based Observations of Satellites from the MOST Microsatellite* DRDC Ottawa TM 2006-199; Defence R&D Canada – Ottawa.

Sommaire

Le 12 octobre 2005, le microsatellite MOST a marqué un tournant dans les opérations de surveillance de l'espace par le Canada en effectuant les premières observations spatiales canadiennes d'un objet en orbite terrestre. Deux satellites de géolocalisation GPS ont été suivis à l'aide du télescope optique monté sur le microsatellite MOST.
MOST est un microsatellite de l'Agence spatiale canadienne (ASC) conçu pour faire des observations photométriques très précises d'étoiles brillantes, et est le premier microsatellite à être doté d'un système de commande d'attitude (ACS) à très grande stabilité (3 secondes d'arc). Le MDN et Recherche et développement pour la défense Canada s'intéressent aux plateformes spatiales de surveillance de l'espace (SAPPHIRE et NEOSSat) et examinent les possibilités des technologies et systèmes utilisés sur l'engin spatial MOST. À titre de mesure de réduction des risques pour le PDT HEOSS, l'Agence spatiale canadienne a autorisé un test utilisant MOST pour tenter de détecter des satellites dans l'espace lointain à l'appui de ces projets du MDN et de RDDC.

MOST a observé le satellite GPS IIR-11 (n° SSN 28190) à une distance de 23 000 kilomètres. Ce fut la première observation depuis l'espace d'un autre engin spatial par un microsatellite. Le jour suivant, MOST a répété l'opération avec succès en observant le GPS IIR-04 (n° SSN 26360). Les deux images étaient d'une bonne qualité, et les deux étoiles et les traces des satellites étaient bien visibles sur les images.

On a établi que les mesures de la position orbitale des satellites ciblés avaient une précision quadratique moyenne de 13 secondes d'arc, ce qui est au delà des objectifs de performance des programmes NEOSSat et Sapphire, mais néanmoins excellent parce que MOST n'a pas été conçu pour produire des images de satellites et encore moins pour suivre des satellites. On explique la plus grande partie de cette incertitude par l'incertitude des systèmes de chronométrage à bord de MOST. L'exploitant de l'engin spatial estime que l'incertitude de chronométrage à bord du microsatellite est de 100 millisecondes; l'analyse des résultats porte à croire qu'elle pourrait être voisine de 300 millisecondes et qu'elle est probablement due à un effet systématique non modélisé dans le processus d'acquisition des images.

Les GPS observés étaient bien éclairés et, d'après les mesures effectuées par MOST, leurs magnitudes astronomiques étaient de $12{,}1 \pm 0{,}2$ et $11{,}5 \pm 0{,}1$, respectivement. Cette magnitude spécifique à MOST est sensible au rouge. La luminosité du fond du ciel a également été déterminée et est de 18,2 magnitudes/(seconde d'arc)^2. Ce fond brillant est peut-être causé par une fuite de lumière dans MOST ou par la diffusion du clair de Terre. Ces deux facteurs doivent être pris en considération lors de l'observation de satellites parce que la lumière parasite du Soleil ou de la Terre crée dans le détecteur un niveau de bruit qui peut dominer le signal du satellite ciblé.

Ce test montre que l'instrument MOST et l'ACS sont prometteurs sur le plan technique comme système de surveillance spatiale. Bien que celui-ci offre une *stabilité* de l'ordre de la seconde d'arc, l'*agilité* exigée de l'ACS pour la mission NEOSSAT n'a pas été qualifiée. Si d'autres tests étaient autorisés, ils devraient tenter d'évaluer approximativement l'agilité de l'ACS en faisant passer l'instrument d'observation d'un satellite à l'autre en succession, et en verrouillant chaque fois un pointage précis.

Scott, R.L.2005. *Space-Based Observations of Satellites from the MOST Microsatellite* DRDC Ottawa TM 2006-199; R & D pour la défense Canada – Ottawa.

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1. Introduction

The Canadian Forces is renewing investment in systems for space surveillance. The Surveillance of Space project (SofSP) is procuring the Sapphire spacecraft, a satellite to conduct operational tracking of Earth orbiting objects. In addition, a joint project between DRDC Ottawa and the Canadian Space Agency has been established to procure a microsatellite to conduct space surveillance of artificial satellites and Near Earth Asteroids (NEAs). This microsatellite will be known as NEOSSat (Near Earth Orbit Surveillance Satellite).

Some key technologies to accomplish both the Sapphire and NEOSSat objectives exist on the Canadian MOST microsatellite. MOST is an astronomical science microsatellite designed to conduct precision photometry on bright stars. MOST uses a precision attitude control system (ACS) and optical telescope system to conduct its observations, both of which are necessary to conduct the space surveillance and asteroid detection missions.

On October 12^{th} and 13^{th} 2005 the MOST spacecraft conducted a test that achieved the first space-based metric observations of satellites from a Canadian microsatellite platform. Good results were obtained despite the fact MOST was not designed to image star fields let alone conduct satellite tracking. While this capability has been proven on larger spacecraft [1], the ability to do so on a microsatellite had not been demonstrated. This test proved that astrometric quality data can be obtained from a microsatellite platform. The background and motivations for attempting these tests are summarized in the following subsections and a brief description of MOST is included. The experimental setup and results from these tests are analysed in sections two through eight.

1.1 Space Surveillance

Since the launch of Sputnik in 1957, Earth orbit has been steadily populated by spacecraft from many nations. As a consequence, Earth is now surrounded by a swarm of satellites and associated debris known as resident space objects (RSOs). Current estimates for the number of these objects are approximately 10,000, of which 7% are useful, active satellites. The remainder of these objects were either decommissioned years ago, or were disposed of after completion of the spacecraft launch. All RSOs will orbit the Earth in perpetuity or until re-entry into Earth's atmosphere.

Space Surveillance is the detection, tracking, propagation of orbital parameters, cataloguing and analysis of these artificial Earth RSOs and is the crucial element of effective operations in space [2]. Satellite orbits evolve in very complex ways due to drag, Earth oblateness, tides and solar radiation pressure. Earth orbiting objects therefore require persistent updates of orbital positions by obtaining position and time (metric) data from observations using ground (and sometimes space-based) sensors. These observations are used to update the orbital elements (elsets) of these objects to keep orbital parameters current.

Aside from spacecraft operational issues, this metric orbital data is required to avoid:

- Possible collision with manned or high-value unmanned spacecraft

- Loss of communication with active spacecraft.
- Re-entering Earth's atmosphere and mistakenly triggering a nation's strategic missile response.

The entity which maintains the most comprehensive catalog of satellite orbital data is the U.S. Space Surveillance Network (SSN) which is now headed by STRATCOM. Other organizations that catalog debris and other satellites include NASA, the Russian Space Surveillance System (RSSS) as well as organizations in a handful of other countries [3]. Canada, under the NORAD agreement, contributes to the U.S. SSN by providing staff and, at one time, orbital observations to assist space surveillance. As a space faring nation, Canada has enjoyed space situational awareness by contributing to this alliance.

SofS employs a variety of sensor platforms such as radars, optical telescopes and laser ranging systems. Radar fills the bulk of this role for Low Earth Orbiting objects (LEOs) as the observations provide accurate range measurements. Radar suffers from $1/R^4$ signal power losses between signal transmission, reflection and reception, making detection of distant deep-space spacecraft difficult. Optical telescope systems have been employed successfully for many years to detect deep-space satellites as they detect reflected sunlight, so no active illumination is necessary for the telescope to see its target. Despite these good qualities, optical systems can only operate at night, only see satellites geographically above them (similar to radar), and need excellent, clear skies to take observations.

The Canadian Forces (CF) is pursuing the development of optical sensor systems for making satellite observations. Optical space-based systems have been deemed to be a good match between Canada's industrial capability and the usefulness of the data to the SSN.

1.2 Optical Space Surveillance Sensors in Space

While optical Space Surveillance systems on the Earth's surface are productive sensors for space surveillance, there are significant advantages to placing an optical space surveillance sensor in Earth orbit:

The sensor is orbiting high above unfavourable weather. (above the clouds and rain within the Earth's troposphere)

The sensor is not geographically restricted and has visibility to nearly all satellite orbits. (Ground based observers can only see satellites directly above them.)

The sensor can operate continuously, not only at night as for ground based optical sensors.

In 1996, the SBV sensor [4] on-board the Midcourse Space eXperiment (MSX), MIT Lincoln Lab demonstrated the utility of optical telescopes for space surveillance. Since that time, SBV has made a beneficial impact on the space surveillance community as the observations have resulted in a marked improvement in element set accuracy [5]. MSX was added to the U.S. Space Surveillance Network as an operational sensor in 1998 and has obtained satellite observations successfully for years. As of this writing, MSX is nearing its end-of-life and replacement systems are being developed.

The Department of National Defence (DND) has created the Surveillance of Space Project (SofSP) to procure a space-based sensor called Sapphire. Sapphire is designed to conduct orbital observations of deep space satellites using an optical sensor mounted aboard a small satellite. The U.S. has also established the Space Based Space Surveillance program (SBSS) to conduct satellite observations as follow-on to MSX. In addition, a DRDC technology demonstration project (TDP) named HEOSS (High Earth Orbit Space Surveillance) has been established to observe satellites and Near-Earth Orbit asteroids. In this TDP, a microsatellite is employed as a low-cost means to observe satellites in support of DND's goals.

1.3 Microsatellites

Microsatellites are a paradigm shift in the way spacecraft are constructed operated and managed. Traditional spacecraft cost hundreds of millions of dollars and weigh ~1000 kilograms or heavier. Microsatellites are physically much smaller, weigh ~100 kg or less, and cost on the order of ten million dollars. Microsatellites generally have few science payloads, minimizing team sizes needed to build and run the microsat program. Microsatellites benefit from higher use of reliable, industrial, commercial off the shelf (COTS) parts and are less complicated spacecraft to construct. As a result, they are less costly to launch and operate.

The CF, faced with realistic budget constraints, see microsatellites as a potential candidate for future defence needs. Microsatellites however, are relatively new and remain unproven as reliable, operational systems to provide data to CF users. A TDP program (HEOSS) has been established to address the military utility of microsatellites and is partnered with the Canadian Space Agency's generic microsatellite bus program. The mission's objective is to conduct space surveillance R&D with the lowest cost space platform possible (NEOSSat). The purpose of HEOSS is to demonstrate the ability of microsat platforms to perform surveillance of space and demonstrate that they have low cost, are military responsive and have military utility. NEOSSat will also be used by CSA to detect Earth orbit crossing asteroids (NESS mission– Near Earth Space Surveillance) to support Canadian space scientists.

1.4 MOST

The MOST (**M**icrovariability **O**scillations of **ST**ars) microsatellite was launched from Plesetsk, CIS in June 2003 aboard a EurRokot launch vehicle. The spacecraft was developed by a consortium of Canadian Industry, Academia and the Canadian Space Agency. MOST is sometimes referred to as Canada's "Humble Space Telescope" as the spacecraft is a tiny device weighing 54 kilograms.

MOST is an astronomical science spacecraft. The spacecraft's mission is to conduct high precision, optical, photometric measurements of bright stars[6]. This type of research permits astronomers to detect the presence of oscillations within stars. MOST allows astronomers to view some stars continuously for up to eight weeks, whereas similar observations from the ground are interrupted by the day-night cycle. This type of continuous viewing ability allows the precise detection of long period, time-trended, variability of a star's light to an unprecedented degree.

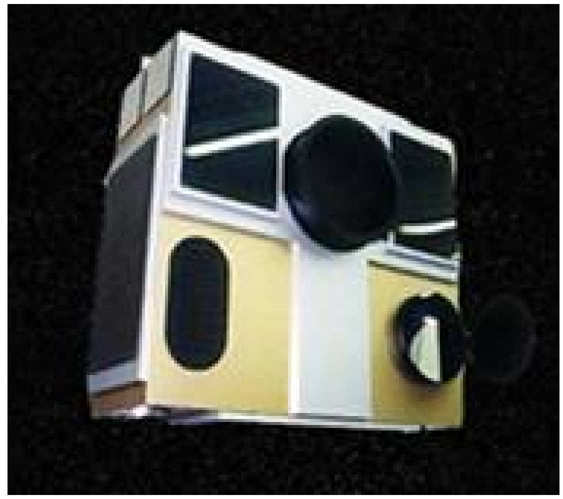


Figure 1. (Left) MOST microsatellite and telescope (foreground) with principle investigator Jaymie Matthews. The MOST microsatellite artistic rendition (right) Image credits http://www.astro.ubc.ca/MOST/media_pack/

MOST was launched into an 830-kilometer, Sun-synchronous, dusk-dawn orbit inclined at 98 degrees. This orbit permits the spacecraft to continuously observe stars in a region of space known as the continuous viewing zone (CVZ) (figure 2). The CVZ is a conical region of space aligned with MOST's orbital pole which always has visibility to deep space. Earth never blocks this region and permits the long duration observing campaigns undertaken by MOST.

MOST is 3-axis stabilized using its telescope as both a precision star-tracker and science instrument. The attitude control system uses magnetorquers and control wheels to dampen attitude jitter and drift to less than three arcseconds [7]. The spacecraft transmits photometry data to the science teams through three ground stations, located at the University of British Columbia (UBC), The University of Toronto Institute for Aerospace Studies (UTIAS) and a cooperative ground station in Vienna, Austria.

MOST is 650 x 650 x 300 millimetres in size, similar in dimensions to a suitcase. The MOST instrument is a 15 centimetre Maksutov-Cassegrain telescope which utilizes a periscope mirror to extend the telescope's focal length. A pair of Marconi 47-20 CCDs is affixed to the instrument focal plane forming the science imager and star tracking detectors. A broadband filter and fabry lenslet array spread starlight over hundreds of pixels in order to accurately measure stellar flux from stars. By spreading starlight over many pixels MOST can measure starlight from bright stars without saturating the CCD and reduce the impact of pixel to pixel sensitivity variations during precise photometry measurements [8].

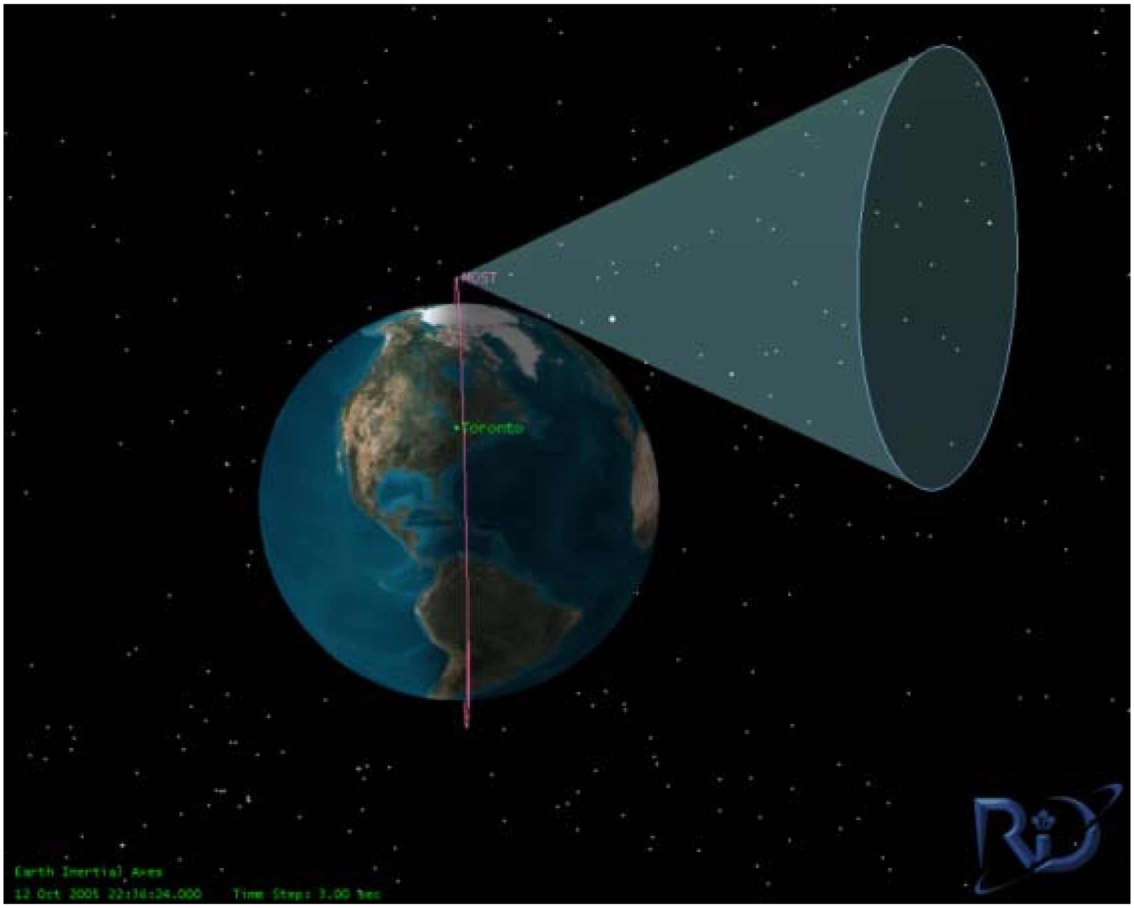


Figure 2. MOST Orbital Geometry showing the continuous viewing zone (CVZ). The CVZ grazes the Earth’s limb but does not intersect it, allowing MOST to continuously observe stars within the CVZ cone. MOST is in a 98 degree inclination, 830 kilometer dawn-dusk Sun-synchronous orbit.

1.5 Chronology of Space Surveillance Testing Using MOST

DRDC Ottawa is active in the area of space surveillance research including the development of the Surveillance of Space Project Concept Demonstrator [9] for the SofSP project and are partners with the Canadian Space Agency in the HEOSS TDP through the NEOSSat Joint Project Office. As a measure of risk reduction for HEOSS an informal request to use MOST for satellite tracking was made to representatives at the Canadian Space Agency in early 2004. Since MOST is an operational science microsatellite there was little immediate interest in pursuing tasking that was not part of the original science mission.

After the establishment of the NEOSSat joint project office, the CSA engaged DRDC in risk reduction for the NEOSSat program by permitting the MOST satellite tracking tests. In early December 2004 an opportunity to attempt satellite tracking during a gap between target science stars was approved by the CSA. This opportunity arose as the MOST satellite operator (Dynacon Incorporated) regularly performs maintenance and software updates on MOST in between science target-star observations. This maintenance period occurs about every ~7-8

weeks. In this instance, additional time was available to perform additional imaging tasks before control was returned to the astronomy science team.

DRDC Ottawa provided a set of look angles, (a prescription of where and when to point the spacecraft camera to take a picture; see section 3) and an imaging attempt was made. MOST failed to take the image due to groundstation command upload difficulties. Four other attempts ensued, all failing due to a combination of ground station problems and the non-standard mode of operation. Another opportunity was provided in May 2005, but the MOST science team requested a priority star transition, pre-empting space surveillance opportunities at that time.

Table 1. *MOST Space Surveillance Attempts 2004-2005*

DATE	RSO TARGET	RESULTS	COMMENTS
03 Dec 2004	GPS IIR-02	FAILED	Ground station command did not upload to spacecraft
11 Feb 2005	Intelsat 901	FAILED	Image was taken by MOST but was immediately overwritten by a subsequent image
14 Feb 2005	Eutelsat W4, Skynet 4F	FAILED	Power failure at Ground station, command did not upload successfully to MOST.
03 Mar 2005	CIS-Block DM	FAILED	Vienna ground station did not achieve MOST acquisition of signal (AOS).
12 May 2005	-N/A-	-N/A-	MOST transitioned to new priority target star Imaging opportunity was removed by MOST Science team
12 Oct 2005	GPS IIR-11	SUCCESS	First tasked acquisition of another satellite taken from a Micro satellite
13 Oct 2005	GPS IIR-04	SUCCESS	Second successful acquisition of a satellite in deep space

On the fifth and sixth attempts MOST successfully tracked two GPS spacecraft. This marked the first Canadian-led, space based tracking of satellites and the first anywhere from a microsatellite platform. The objectives, experiment setup, access particulars, metrics, photometry and a sampling of some telemetry taken from MOST during this experiment are discussed in the following sections.

2. Space Surveillance Objectives Using MOST

It was agreed that since MOST is an operational science microsatellite any space surveillance activities must be benign and neither interfere nor hinder MOST's normal space-science operations. A list of basic test objectives was formed by DRDC Ottawa for any testing performed by MOST (Table 2). These objectives focused on risk reduction for HEOSS.

Table 2. *Test Objectives – MOST Space Surveillance Activities*

Primary Objectives	-Maintain fine-pointing attitude lock and take an astrometric-quality image of deep space while a satellite/RSO target flies through the field of view -Verify approach to scheduling space-based satellite observations
Secondary Objectives	-Ascertain metric data quality from any successful images -Determine photometric brightness of the target satellite and estimate its quality -Characterize factors limiting instrument sensitivity -If possible, conduct an observation of a different spacecraft target

The overarching, primary objectives were to validate that a microsatellite can produce high quality star field images enabling the detection and measurement of a deep space satellite target's position. Equally important was the verification of the technique used in the planning of the satellite-target observations. A success in both of these primary objectives helps retire risk for the NEOSSat spacecraft.

Secondary objectives come into play only if a useful observation resulted from the first satellite tracking attempt. "Metric data quality" quantifies the accuracy of the measured position/time data and identifies the sources of error incurred during this test. "Photometric brightness" provides an estimate of the observed satellite brightness as measured by MOST and estimates the measurement error. "Characterize factors limiting instrument sensitivity" identifies the issues limiting the ability of a MOST-class instrument to detect faint target satellites. Naturally, a second observation would help reduce the possibility of beginner's luck if the first observation was a success.

3. Experiment Planning

The end product of the observation planning process is a set of look-angles and the exposure start and duration times during which MOST can "see" a distant satellite. These look-angle parameters detail how MOST should be oriented in space, when the instrument should start taking an image and for how long. This requires several geometric constraints to be considered, including the restriction that MOST cannot be pointed outside of the CVZ. Look angles are sent to the spacecraft operator who converts them to spacecraft commands and transmits them to MOST.

The following steps were followed when planning an observation.

- Satellite operator notifies CSA/DRDC Ottawa of an imaging opportunity (~1 month in advance) DRDC applies to CSA for approval to proceed. CSA liaises with UBC and grants/denies experiment time with MOST.

- The satellite operator and UBC provide a plot of a recommended observing region inside the "Continuous Viewing Zone". The time(s) of the MOST to Dynacon access is also provided in order to constrain when the image can be taken. This information is sent to DRDC Ottawa.

- Using the CVZ recommendation and access time(s), DRDC Ottawa opens a computer simulation of the MOST-target access. This scenario models the orbit and CVZ geometry for the date of the access opportunity. The orbit is updated with the latest element sets for the MOST spacecraft.

- DRDC Ottawa creates a "Deck-Access" in STK (an Astrodynamics simulation software) which generates a lengthy list of candidate deep space spacecraft which fall in the CVZ during the access window.

- DRDC Ottawa checks that the candidate spacecraft 1) are inside the recommended CVZ zone, 2) is favourably illuminated and 3) angular rate relative to MOST is low. DRDC parses the candidate list and seeks one or two candidates (GPS or large geostationary spacecraft) that are likely to be visible during tracking. A short ephemeris relative to MOST is generated consisting of Universal Coordinated Time (UTC), right ascension (RA), declination (DEC) and range. RA and DEC are celestial coordinates tied to an inertial frame.

- DRDC Ottawa sends the candidate list of look angles to the satellite operator. The operator verifies that the spacecraft fall within the CVZ and that sufficient guide stars are available in order to establish fine pointing lock. If ok, the spacecraft are selected, DRDC is informed that the candidate targets are valid, and the MOST-Access simulation is saved.

- One Day prior to observing, DRDC Ottawa updates the MOST-Access scenario with refined access times (MOST to ground station) and the latest two-line-element sets for MOST and target RSOs. The look-angles are updated, marked as "actionable" and are sent to the satellite operator. The satellite operator converts the look angles to spacecraft instructions and uploads the desired attitude (RA,

DEC, Roll) and exposure time initiation for the camera. The commands are uploaded on the first available access opportunity.

- MOST slews to the targeted attitude and holds fine-pointing lock for several orbits. MOST's CCD camera takes a snapshot using a time-tagged command.
- The image is stored to memory and downloaded to the ground station on subsequent passes. The satellite operator informs DRDC if the image attempt was successful.
- The data is packaged in a standard file format for astronomy images and are passed to DRDC for analysis.

The geometric and physical aspects that must be considered during imaging are the topic of the next section.

3.1 Physical Constraints on MOST for Satellite Tracking

There were several physical constraints which need to be respected in order to conduct an acquisition of a satellite target with MOST. They are:

1. Imagery has to be acquired in star-stare mode (SSM). In this mode MOST is inertially-fixed with respect to the stars and the observed satellite streaks through the telescope field of view. This is consistent with the normal mode of operation of MOST.

2. MOST was not designed to image large star fields, thus MOST does not have sufficient memory to store multiple large images. MOST can store only one starfield image at a time, and takes approximately two orbital revolutions to download an image to its ground station.

3. The tracking attempts would only take place during the star transition periods when the satellite operator is in control of the spacecraft.[*] MOST needs to be in sight of a MOST ground station to be issued spacecraft commands.

4. MOST must look anti-sunward within the CVZ of the spacecraft. No look can be made outside of this zone as the spacecraft would point its star tracker towards the Earth at some point in its orbit and lose fine-pointing mode star lock.

5. The images must be taken well above Earth's limb and its associated scattered sunlight. MOST has a limited stray light rejection capability so the instrument boresight must be well elevated above the Earth limb.

6. A light-leak onboard the MOST spacecraft further restricted the areas which MOST can look. The MOST/Dynacon team provided a CVZ recommendation (figure 3)

[*] This condition was later relaxed as software upgrades now permit MOST to take a stored time-tagged image command at any point without need line of sight to a ground station.

where the instrument would be less susceptible to Earth limb stray and leaked light through the body of the spacecraft.

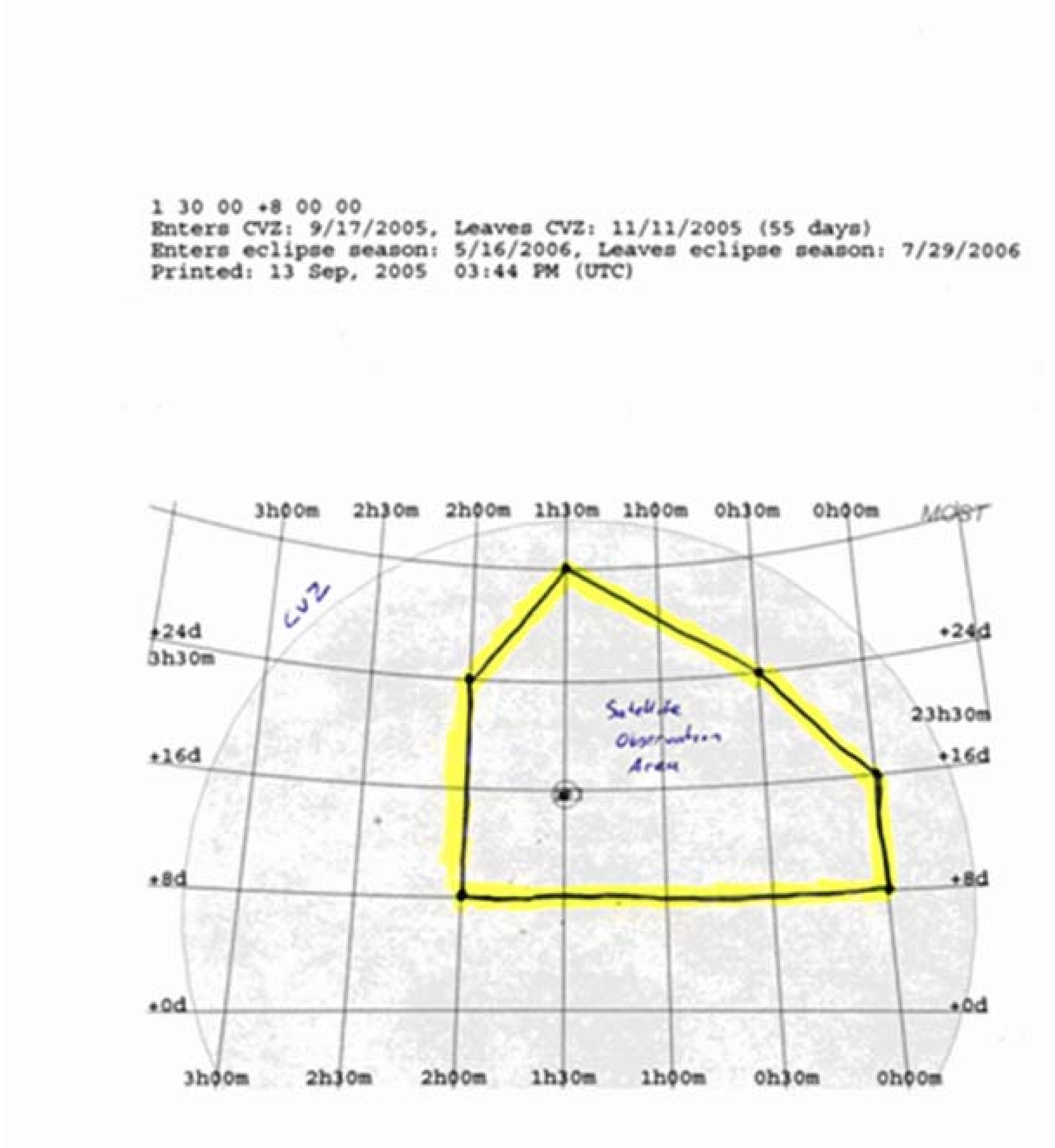


Figure 3. MOST CVZ recommendation during satellite access attempts. Right ascension is the horizontal axis. Declination is the vertical axis. At the time of observation, MOST's nadir vector is pointing in the direction of ~3h00, +0d relative to the center of the CVZ.

7. MOST cannot take its image during traversal of the South Atlantic Anomaly (SAA). The high concentration of energetic protons in this region creates a high number of false counts and streaklets on the CCD detector making satellite detection difficult.

8. There are two pertinent access constraints between the MOST-target pair. First, the target satellite must be fully illuminated (i.e. outside of eclipse). Seconds, the relative angular rate of the target spacecraft must fall within a certain range: if it is too slow, the target appears motionless and appears like a star making identification difficult, if it is too high, it will streak through the field of view without sufficiently illuminating MOST's CCD pixels.

These conditions limit the number of satellites that can be detected and when these satellites can be detected. With these constraints in mind, DRDC searched for candidate deep-space satellites which could be observed by MOST. The constraints were modeled within the STK simulation to determine the best candidates target satellites for the MOST tracking experiment. A quantitative list of these access constraints are listed in Annex A.

3.2 Selection of Target Satellites

In order to find candidate spacecraft DRDC Ottawa performed a deck-access using STK. This simulation finds all objects falling within a conical CVZ volume with respect to MOST while respecting the physical constraints detailed above. A candidate list was formed by finding all unclassified deep-space satellites which fell within this simulated CVZ cone and also falling within the recommended observing region suggested by UBC during the recommended observing times.

During the first tracking opportunity, there were 14 deep-space candidates which fell within the recommended region CVZ (figure 4). Most of these spacecraft were rocket bodies and transtage debris. These candidates were ignored as debris tends to tumble causing them to erratically change brightness. Debris objects also tend to be in eccentric orbits which usually have elsets of lesser quality and are less frequently updated by the SSN. The resulting ephemeris error makes it less likely that they would fall within MOST's small sensor field of view.

Fortunately, an operating GPS spacecraft (#28190) entered the recommended CVZ just at the beginning of the access interval on 12 Oct 2006. GPS spacecraft are excellent candidate targets as they follow near circular orbits, have very accurate orbital ephemerides, and have been well studied by ground based observers. GPS are stabilized, have large solar panels and vary their brightness predictably during observation.

An identical approach was used to determine the candidate list for the second attempt on the following day. Again, debris were ignored and another GPS spacecraft was serendipitously in the field of view at the time of access.

Figure 4. Looking down MOST's CVZ – the recommended observing region (yellow) is overlaid onto the actual CVZ with the position of deep-space spacecraft at the beginning of access indicated by the colored dot and labels. The concentration of spacecraft towards the bottom of the frame is a small sector of the geostationary belt. Celestial North is towards the top of the image

3.2.1 GPS Candidate Targets

GPS (Global Positioning System) is a constellation of 24 NAVSTAR (NAVigation Satellite Timing) spacecraft owned and operated by the U.S. Department of Defence. These satellites are radio beacons which broadcast their position via L1 and L2 radio frequency bands to sea, air and ground-based users. As GPS positioning accuracy demands are high, the reference orbits used in the broadcast of the GPS satellite's ephemeris require sub-meter accuracy. End –user GPS radio receivers provide navigation solutions accurate to within 10 meters. GPS satellites are useful to the Space Surveillance community as calibration targets due to their high accuracy orbital ephemerides. Space Surveillance measurements are often compared to the 'truth' or reference orbit positions of the GPS spacecraft giving sensor operators an external reference in which to calibrate the accuracy of their systems.

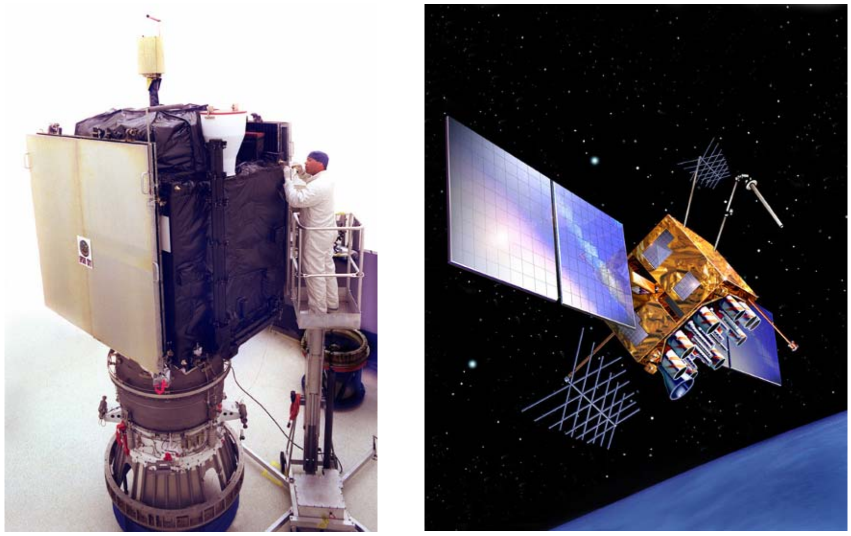


Figure 5. GPS Block IIR spacecraft (SV11). Image credit Lockheed Martin Corporation

Both GPS spacecraft observed by MOST were of similar construction. GPS IIR-04 is a Block IIR NAVSTAR satellite launched in May 2000; GPS IIR-11 was launched in March 2004. Block IIR GPS spacecraft feature a box-wing design where a central bus and bulkhead comprises the physical structure of the spacecraft and two large deployable solar panels (~10 m^2) comprise the power generation system for the satellite (Figure 5).

GPS have orbital periods of 12 hours, lending themselves well to repeat observations from ground based sensors. The spacecraft reappear in nearly the same area of sky from night to night and slowly migrate out of view. This allows repeat observation attempts if weather or equipment problems prevent operation on a given evening.

For space-based observation, GPS make excellent targets because:

- GPS satellites have orbits with a semi-major axis of ~26,400 kilometres. This reduces the effect of high order zonal and tessoral gravitational anomalies and places them beyond the atmospheric drag regime. This in turn makes orbit prediction easier and elsets remain valid for a longer period of time. This increases the likelihood that the GPS spacecraft will be in MOST's field of view at the time of acquisition.

- GPS operators publish reference orbit ephemerides accurate to within 1 meter. This provides an excellent external reference to determine the accuracy of a space-based metric observation.

- GPS are fairly bright, and are three axis-attitude stabilized. Phase-magnitude data for these spacecraft are well studied [10] increasing the likelihood that the spacecraft would be detectable to the MOST sensor as its brightness can be predicted in advance. This also provides a means to evaluate the ability of MOST

to measure the brightness of the GPS by comparing MOST photometry observations to ground based photometric observations.

Block IIR GPS satellites are 'newer' versions of GPS and are manufactured by Lockheed Martin. When observed on-orbit, these spacecraft are fainter compared to their earlier Block II/IIA cousins for a given range, phase angle and orientation. Block IIRs have a black kapton covered bulkhead causing most of the reflected sunlight to be emitted from the solar panels. The Block II and IIA GPS reflect sunlight from both the solar panels and from the more-reflective bulkhead of the spacecraft.

3.3 Selecting the MOST Exposure Duration

Proper exposure of the MOST instrument must be undertaken as a target satellite signal can be swamped by thermal, read noise and background sources by exposing the CCD too long during SSM tracking. This is counterintuitive [11] as normal astronomical images benefit from increased exposure time. Rapidly moving objects only expose a small region of pixels for a short time, and move quickly to neighbouring pixels. As a CCD builds dark current, background and system noise during the exposure, this has the effect of drowning a satellite's signal strength within sensor and background generated noise. This is often known as "trailing loss" when tracking a fast moving object. For the MOST sensor a 3-4 second exposure was considered to be optimal.

In this experiment, there was some uncertainty as to whether or not MOST would even target the correct region of space during the exposure. It was expected that small 10x2 arcmin (200x40) pixel subrasters would be used in order to take the two tracks. To increase the likelihood of seeing a streak on the subrasters, the exposure times were lengthened to 5 and 7 seconds. As many spacecraft experience along-track position errors increasing the exposure length improves the likelihood that MOST would see the targeted spacecraft on the subrasters. This would create a longer, faint streak, but it would still be discernable by a human eye.

When the data was returned to DRDC, the experimenters were pleasantly surprised to see a 14x48 arcminute (280 x 960 pixel) field of view. With a field of view of this size, increasing the length of the exposures would have been unnecessary and the satellite streaks would have benefited from a reduced exposure duration, increasing the detected satellite's signal to noise ratio.

3.4 The Look-Angle Product

After the spacecraft attitude, exposure time and duration were determined, a short list of MOST-centric J2000 time, RA, DEC and range data were sent to the MOST spacecraft operator. The look angles given to the MOST operator are shown in Annex B.

4. Access Particulars (12-13 October 2005)

4.1 Access Overview

As discussed previously, MOST attempted detection of two GPS spacecraft inside the CVZ. Figures 6 and 7 show the relative geometry for the two accesses. MOST was travelling Northward towards Canada and exiting the intense radiation region of Earth's South Atlantic Anomaly (SAA). MOST was locked on the target attitude for at least one Earth revolution prior to its attempt on the first target satellite. The second track was similar, with MOST oriented to a different attitude.

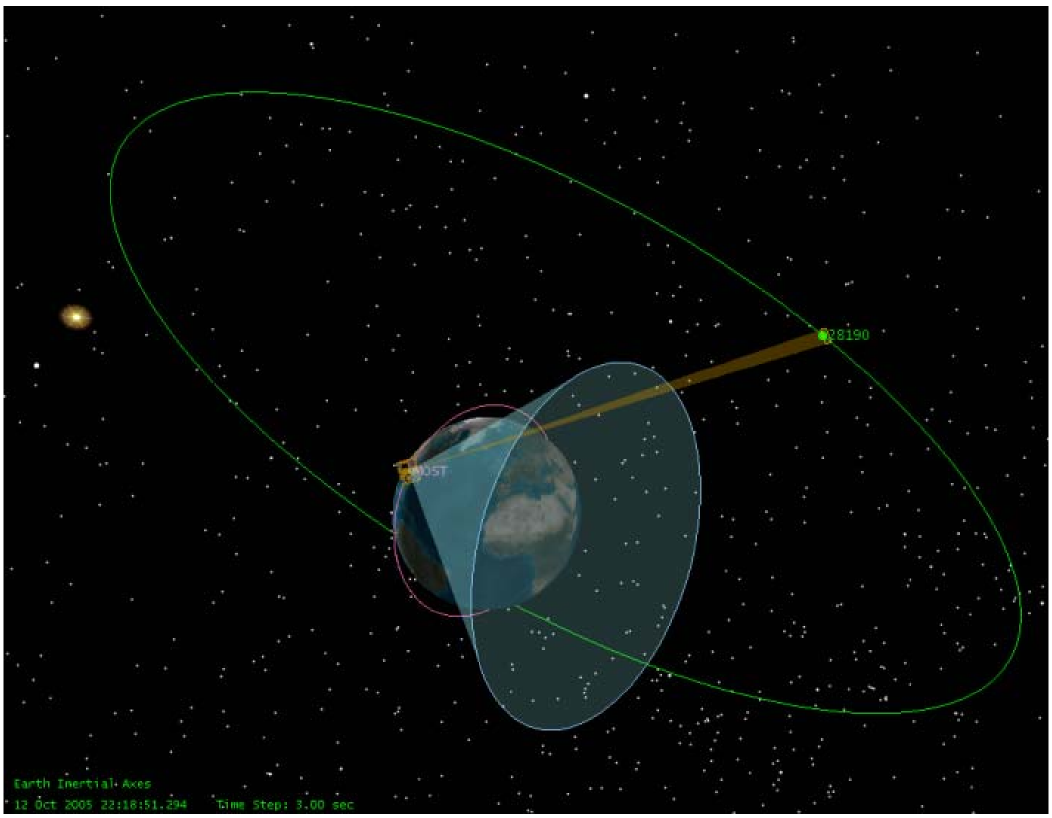


Figure 6. Sun, MOST, Earth, CVZ and GPS target satellite geometry during the first satellite tracking attempt. The CVZ is the blue conical region. (12 Oct 2005). MOST is located on the purple orbit closest to Earth and the GPS is located on the green outermost orbit. The yellow wedge is the telescope's line of sight.

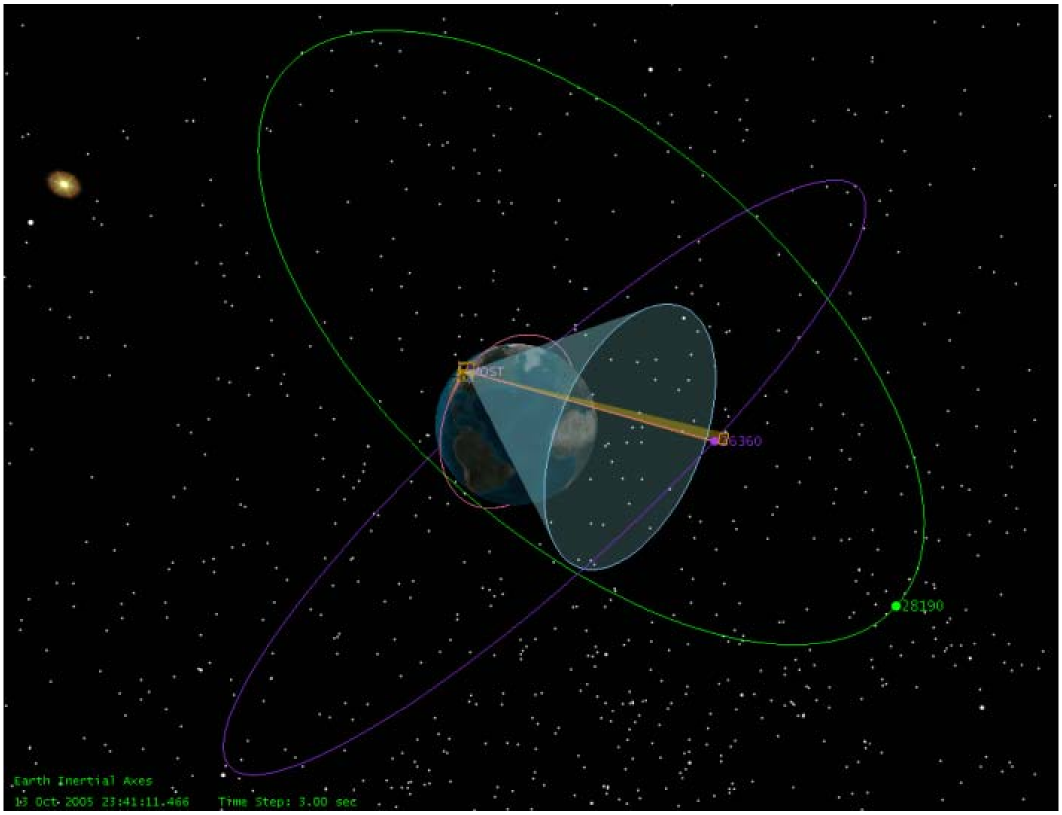


Figure 7. Sun, MOST, Earth, CVZ and GPS target satellite geometry during the second satellite tracking attempt. The CVZ is the blue conical region. The previous satellite target's position and orbit is shown in green for reference. (13 Oct 2005)

4.2 A Note on Seasonal Effects

The satellite tracking experiment occurred three weeks past the autumnal equinox. MOST was traveling about Earth's terminator, slightly above the dark limb of Earth (figures 8,9). If these observations had been taken during the summer solstice MOST would have been flying above an illuminated sector of Earth's surface. The telescope would have 'seen' more of the Earth's illuminated limb and more stray light may have leaked into the optical system of MOST. MOST has a limited capability to reject Earth irradiance as its internal baffle cannot handle observations close to the illuminated sector of Earth's limb.

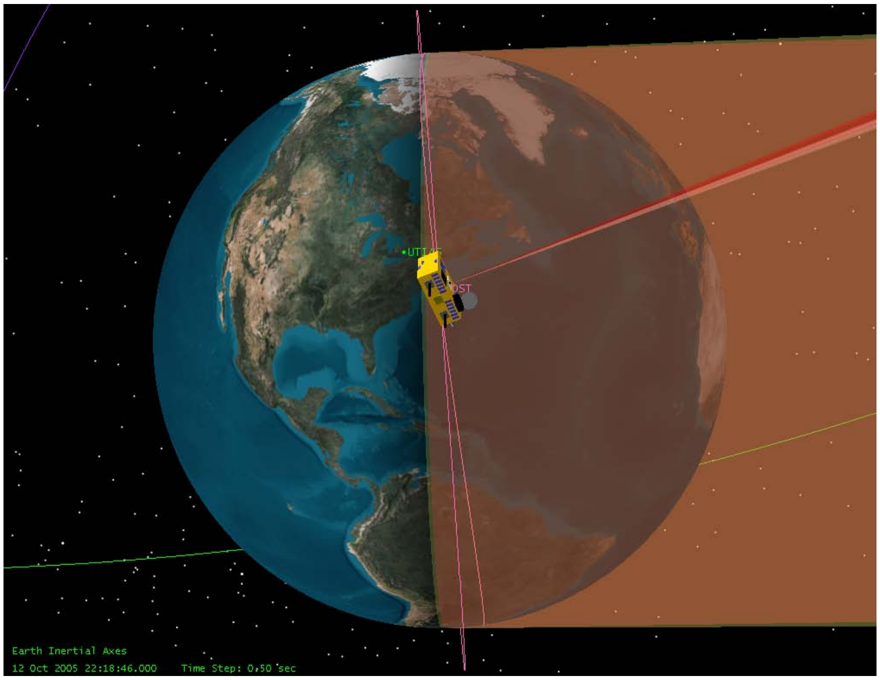


Figure 8. MOST position relative to Earth's terminator. The spacecraft was flying just over the dark limb of Earth at the time of observation.

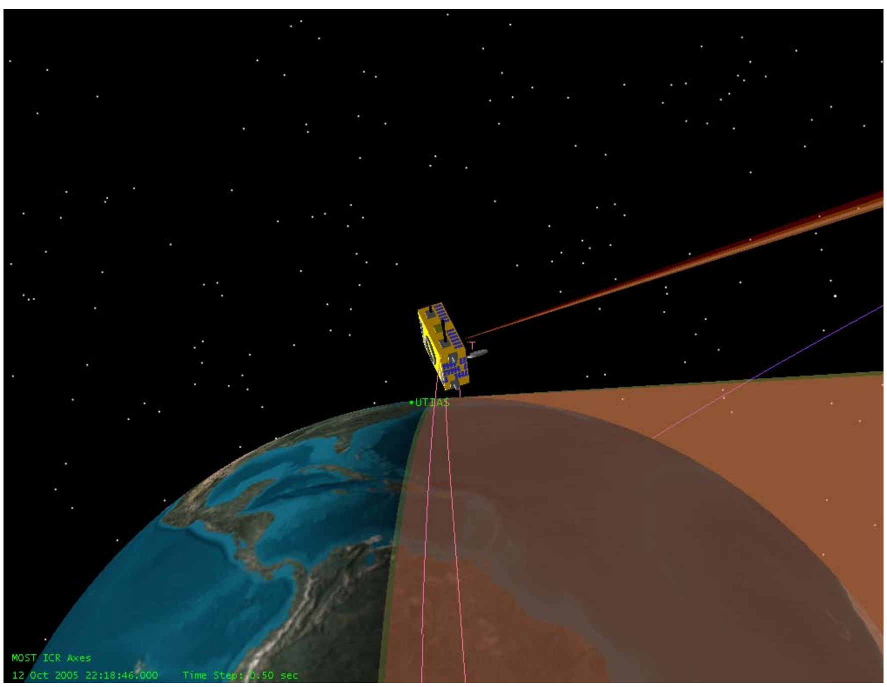


Figure 9. MOST boresight (ray emanating from MOST) position relative to Earth's limb. The Sensor boresight was 41.8 degrees above the nearest tangential point on Earth's limb at the time of the first observation.

4.3 Access Geometry

Both GPS spacecraft were observed under similar geometric conditions relative to MOST, but there are slight differences between the two; a summary of the important geometric parameters are shown in Table 3. Both spacecraft were observed under similar phase conditions and ranges, but the relative angular speeds were considerably different. The first GPS had a relative angular rate of 77 arcsec s^{-1} while the second had an angular rate of 32 arcsec s^{-1}. This directly affects the measured signal strength for a satellite detected using SSM as trailing losses increase with larger relative rates. The slower that a satellite moves relative to an inertially-fixed CCD detector, the stronger the measured signal appears. Since sunlight from the targeted satellite integrates over a smaller, concentrated group of pixels increasing the signal.

Table 3. *Satellite Access Particulars*

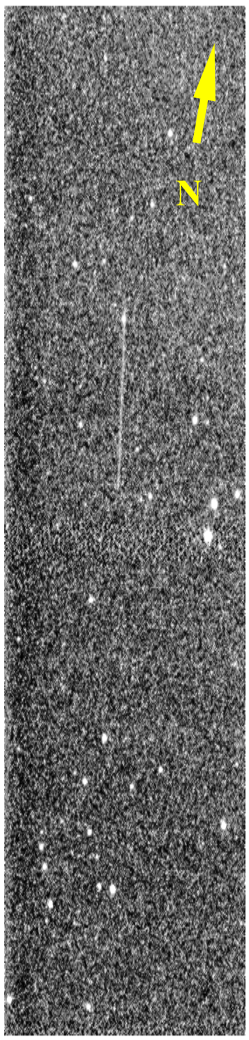
PARTICULARS	1^{ST} TRACK (28190)	2^{ND} TRACK (26360)	UNITS
Target Type	GPS IIR-11	GPS IIR-04	
Range to Target	23,949	23,237	km
Relative Angular Speed (relative to MOST)	76.6	32.4	arcsec-s^{-1}
Phase Angle	21.0	17.1	deg
Exposure Start Time	12 Oct 2005 22:18:46.294	13 Oct 2005 23:41:11.466	UTCG
Exposure Stop Time	12 Oct 2005 22:18:51.294	13 Oct 2005 23:41:18.466	UTCG
Grazing Angle*	41.8	47.2	deg
Target Sun Condition	Direct Sun	Direct Sun	
Boresight Solar Elongation	158.9	162.9	deg
Boresight Lunar Exclusion	73.6	41.3	deg
Lunar Phase	75.5%	85.3%	% Illumination

*Boresight of MOST sensor relative to the limb of Earth.

MOST had line of sight visibility to the Dynacon groundstation during the acquisition. Line of sight was not actually required as a new software patch permitted MOST to execute time-tagged commands in order to trigger the instrument exposure at the correct time anywhere on orbit.

5. Image Data and Astrometric Analysis

The image data sent to DRDC Ottawa were in FITS (Flexible Image Transport System) format files. This is a common file standard used by the astronomical community. The field of view of the sensor was truncated from the full, imaging field (which resembles an L-shape) [8]. The original data sent to DRDC Ottawa required FITS header manipulation to remove a non-existent (NAXIS3) field. After it was removed, the images opened easily in a variety of commercial FITS software packages (MaxIM DL, CCDSoft, FITSView etc). The files from the first and second observations were ~650 kB and 2 MB in size respectively. The second image was a full frame download of the CCD, including the non-imaging area of the chip, accounting for the difference in the size of files. Dynacon indicates that it took two orbital revolutions of MOST in order to download each image through their groundstation.



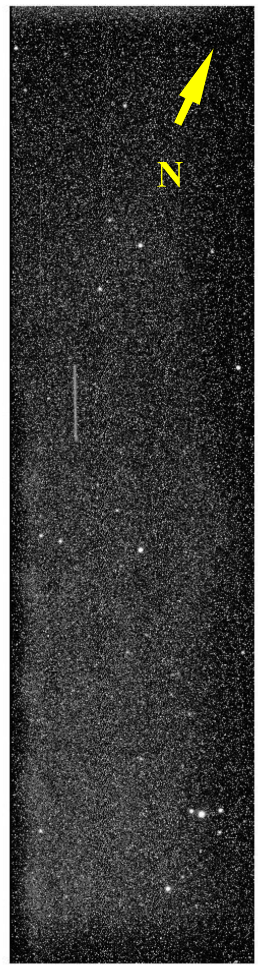
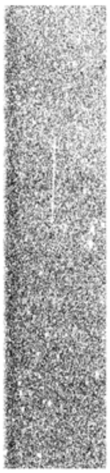


Figure 10. (Left) GPS IIR-11 12 Oct 2005, 22:18:46 UTC. (Right) GPS IIR-04 13 Oct 2005, 23:41:11 UTC. Target motion is from top towards the bottom

5.1 Astrometry Summaries

A picture of satellite streaks and stars is of little value if one cannot associate a geocentric (or sensor-centric) right ascension and declination coordinate to each pixel. Thus, the images need to be 'solved' astrometrically in order to associate pixel positions to celestial (world) coordinates. This is often performed by correlating bright image stars to known star catalog positions and applying a mathematical rule to 'fit' the image to the world coordinate system. A user can then obtain the RA and DEC of any pixel in the field of view after astrometric solution. All star solutions reference the mean equator and equinox of J2000** which has been established as the frame of choice for SSN data analysis software.



1st Track (28190)	
Astrometry Summary	
Number of Solution stars	16
RMS fit residual	0.89 arcsec
Avg. Stellar FWHM	8.6 arcsec
Pixel Scale	2.98 "/pix
Track RA (J2000)	01^h 16' 48"
Track DEC (J2000)	28° 39' 54"

Figure 11 Astrometric Solution Data for 1st satellite track.

2nd Track (26360)	
Astrometry Summary	
Number of Solution stars	10
RMS fit residual	0.7 arcsec
Avg. Stellar FWHM	7.2 arcsec
Pixel Scale	2.98 "/pix
Track RA (J2000)	00^h 17' 06"
Track DEC (J2000)	17° 11' 59"

Figure 12 Astrometric Solution Data for the second satellite track.

The mathematical rule was derived using Pinpoint™ astrometry software. No image adjustments were required in order to solve the plates using Pinpoint. Each star field was

**Astronomers reference J2000 as the mean equator and equinox of Jan 1.5 2000, whereas the SSN references the mean equator and equinox of Jan 0.0 2000 (Dec 31 1999). The corresponding precession error of ~0.2 arcseconds is ignored in this report.

correlated with the Hubble Guide Star Catalog version 1.1. To solve the plates, a seed right ascension and declination must be fed into Pinpoint in order to perform the astrometric solution. The look angles sent to the MOST operators were used to do so.

The measure of quality of the star fit to star catalog positions is determined by finding the RMS residuals from the astrometric solution. The RMS star fit residuals were less than one arcsecond for both images, indicating a good astrometric fit given the astrometry errors inherent in the Guide Star Catalog. The measured pixel scale was 2.98 arcseconds per pixel, consistent with the measures made by University of British Columbia astronomers.

The Hubble GSC 1.1 contains systematic and random position errors (0.5-0.9 arcsec) due to the scanning process used to digitize the photographic Schmidt plates in the construction of the GSC catalog [12]. Thus, ~1 arcsecond of error can be expected due to the systematic errors inherent in the GSC catalog. With more solution stars, the random error component can be reduced by $n_{stars}^{1/2}$, however, the systematic errors tend to dominate star fits when using the Guide Star Catalog.

5.2 Formation of Observations

The astrometric solution provides “MOST-centric, J2000 – apparent” positions of the stars and satellite. Each streak endpoint was manually evaluated as the streaks were too faint for automated streak detection; many automated streak detection algorithms require a minimum “best pixel” signal to noise ratio (SNR) of ~3 in order to reliably detect a satellite [11][13].

The pixel position corresponding to the observed streak endpoint was recorded and converted to J2000, spacecraft-centric RA and DEC. At this point, the observations need to be corrected for annual and orbital aberration. Star catalog positions are referenced to the Barycentre of the solar system, which is considered to be a non-moving frame for space surveillance applications. MOST took its observations from a moving frame as it is moving about the Earth and the Earth is moving about the solar system Barycentre. Starlight observed from this moving frame is shifted due to the finite velocity of starlight and the motion of the observer about the solar system’s Barycentre. The Barycentric, J2000 velocity of MOST was estimated using Satellite Tool Kit (STK), in order to determine the magnitude of correction for this aberration effect [Annex-C].

Once the streak endpoints are corrected for orbital aberration, the image time-tags corresponding to exposure start and finish are married to each endpoint creating ordered pairs of time,RA,DEC. One can now evaluate the accuracy of the measurements by comparing the observations to the reference positions of the tracked spacecraft.

6. Metric Accuracy

Metric accuracy is the quantitative assessment of orbital measurement data quality. In order to determine if the orbital position observations (metrics) are accurate, the positions need to be compared to an external reference. These measurements establish the biases (systematic error) and sigmas (random error) of the data. Once these quantities have been established, evaluation of the quality of the sensor data can then be performed.

6.1 Estimating Metric Error

Von Braun [4] suggested a relationship (Equation 1) to estimate the extent of orbital observation measurement error. This relation is a simple root-sum-square of the various metric error sources, thus independence of the error sources is implied.

$$\sigma_{total}{}^{2} = \sigma_{ephemeris}{}^{2} + \sigma_{timing}{}^{2} + \sigma_{boresight}{}^{2} + \sigma_{SEP}{}^{2} + \sigma_{unknown}{}^{2} \qquad \text{Equation 1}$$

Where σ_{total} is the total angular error estimate, $\sigma_{ephemeris}$ is the parallax error due to the positioning uncertainty of the observing platform, σ_{timing} is the timing uncertainty for an image that is tagged with an exposure start and stop times, $\sigma_{boresight}$ is an aggregate error which estimates the RMS difference of star centroids and star catalog position error, σ_{SEP} is an estimate of the streak-end-point position uncertainty. The quantity $\sigma_{unknown}$ is a blanket term for external factors yet to be established and is ignored in the following error estimates. This estimate can be used for both ground and space-based optical observations of satellites.

6.2 Metric Error Estimate Prior to MOST's Tracking Attempt

Prior to observing the selected GPS satellites, an estimate of the metric error quality for MOST was made (Table 3).

Table 3. MOST Metric Error Estimate

Source	#28190 (1st Track)		#26360 (2nd Track)	
Ephemeris Error	1000m (Slant range 23900 km)	8.6 arcsec	1000m (Slant range 23230 km)	8.9 arcsec
Timing Error	0.1 sec 77 arcsec/s angular rate	7.7 arcsec	0.1 sec 32 arcsec/s angular rate	3.2 arcsec
Boresight Error	GSC limited ~1arcsec	1.0 arcsec	GSC limited ~1arcsec	1.0 arcsec
Streak Endpoint Detection Error	8 Pixel average	4.2 arcsec	8 Pixel average	4.2 arcsec
Total (RSS)		**12.5 arcsec**		**10.4 arcsec**

The metric error from Table 3 was estimated to be ~11.5 arcseconds average. It was therefore anticipated that MOST's metric accuracy during satellite tracking would not meet the performance limits set for Sapphire and NEOSSat (which are 5 and 6 arcsecond error respectively) due primarily to the ephemeris and timing error sources. Validation of the error budget would however lend confidence to the error budget requirements for NEOSSat.

6.3 External Calibration References

In order to establish actual metric quality, observations of calibration satellites are taken by space surveillance sensor operators. Calibration satellites have well-studied orbital motion and repeated observations permit operators to publish orbital ephemerides accurate to within 10 meters. Generally these spacecraft are radar calibration spheres, laser ranging targets (i.e. LAGEOS 1,2) GPS or Tracking and Data Relay Spacecraft (TDRS).

Orbital measurements taken by MOST were compared to GPS reference ephemerides produced by the National Geospatial Intelligence Agency [14]. These orbital ephemerides are produced in an Earth–fixed coordinate frame and require accurate coordinate transformations for precession, nutation, sidereal time and polar motion. These transformations were applied using STK.

6.4 Post-Acquisition Metric Accuracy Summary

With the astrometric star-solution of the images and formation of spacecraft-centric, J2000, aberration corrected observations, one can compare these measurements to the targeted satellite's calibration ephemeris. Data quality is evaluated by forming small angle residuals between the measured and truth positions of the spacecraft in both right ascension and declination. The metric results for both satellite tracks are shown in Table 4.

Table 4. Metric Accuracy, both Accesses

TRACK	ΔRA RESIDUALS (“)	ΔDEC RESIDUALS (“)	TOTAL (“)
1st - 28190	-8.2	-6.0	10.1
1st - 28190	2.1	15.3	15.4
2nd - 26360	-9.9	-12.2	15.7
2nd - 26360	-2.9	0.9	3.0
Bias	***-4.7***	***-0.5***	
Sigma	***5.4***	***11.8***	***13.0***

Metric error residuals (dRA and dDEC). The estimated RMS error for this sample is 13.0 arcseconds.

The “biases” (systematic errors) are calculated by taking the elementary mean of the observation residuals. The “sigmas” (random errors) are calculated by evaluating the standard

deviation for the set. The RMS error (approximated as the root-sum-square) of the sigmas, is 13 arcseconds. This set of data is small so the bias and sigma results are coarse estimates only. An expanded set of observations (30 or more) would be very beneficial in evaluating MOST's ability to take accurate orbital data by allowing proper statistical treatment of the data.

As expected, the MOST observations do not meet Sapphire and NEOSSat's metric accuracy goals but are consistent with expectations for the microsatellite's capabilities. MOST was not designed for imaging let-alone attempting satellite tracking and its performance is on par with expectations.

It should be mentioned that the ephemeris position for MOST was estimated to be approximately 120 meters at the times of both images. This fortunate circumstance occurred due to the SSN updating the elsets for MOST on the same day that the images were taken. Comparing elsets for epoch days 2005-284 and 2005-285, the elsets agree within 120 meters (a full treatment of the elset comparison is in Annex D). This reduces the ephemeris error to less than 1 arcsecond leaving timing error and SEP error as the dominant error sources.

Overlaying the truth positions of the GPS spacecraft on the images and comparing them to the manually determined endpoints, it is observed that the errors are primarily along-track. This suggests that timing uncertainty is the dominant source of error (Figure 13). This error is likely due to an unaccounted systematic effect in the time stamping of the images causing the data to have an along-track error component. This error may also be due to along-track uncertainty in MOST's orbital ephemeris, but is less likely due to the good consistency of the element sets between the observations (refer to Annex D).

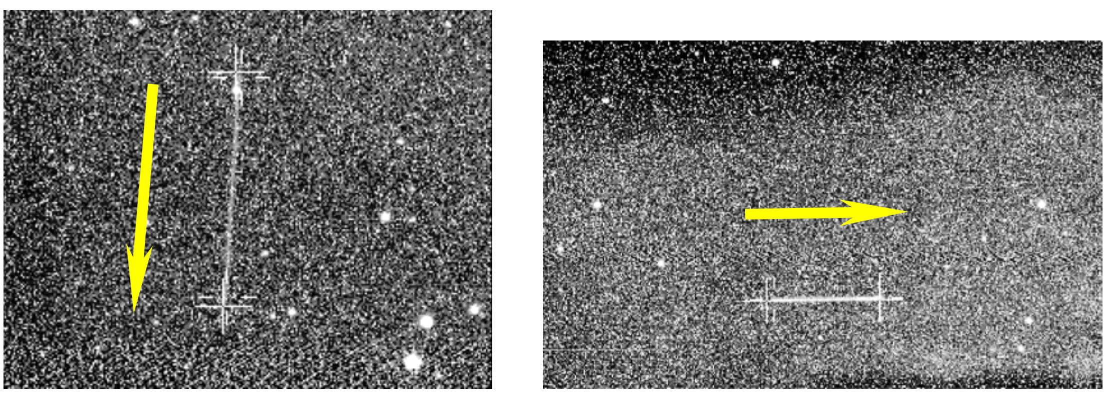


Figure 13. Along track error shown relative to both satellite streaks. The direction of spacecraft motion is indicated. Full crosshairs are the truth position of the spacecraft at the time of measurement. Open crosshairs represent the manually measured streak endpoint.

7. Photometry of Tracked Satellites

7.1 Photometry Calibration

The MOST images not only provide a means to accurately measure the angular position of the targeted GPS satellites, but also a means to measure their brightness. Using the stars in the background sky one can estimate the satellite's brightness by using differential photometry. To do so, a pixel count to magnitude calibration is performed (shown in figure 14). Circular apertures were used in MaxIM/DL[Ψ] to obtain the individual stellar brightness in pixel counts. The signal aperture diameter was set to 3 times the average stellar width, a rule commonly used by astronomers. Correlated stars from the GSC 1.1 were used as reference star magnitudes.

A broad-band filter is used on MOST so conversion to a standard magnitude scale is not possible. The magnitude estimates are therefore a MOST-sensor specific magnitude, but the MOST system throughput peaks near the astronomical V-band due to the introduction of a broadband filter used in the MOST optics cutting long wavelengths to less than 50% at 700 nm [8].

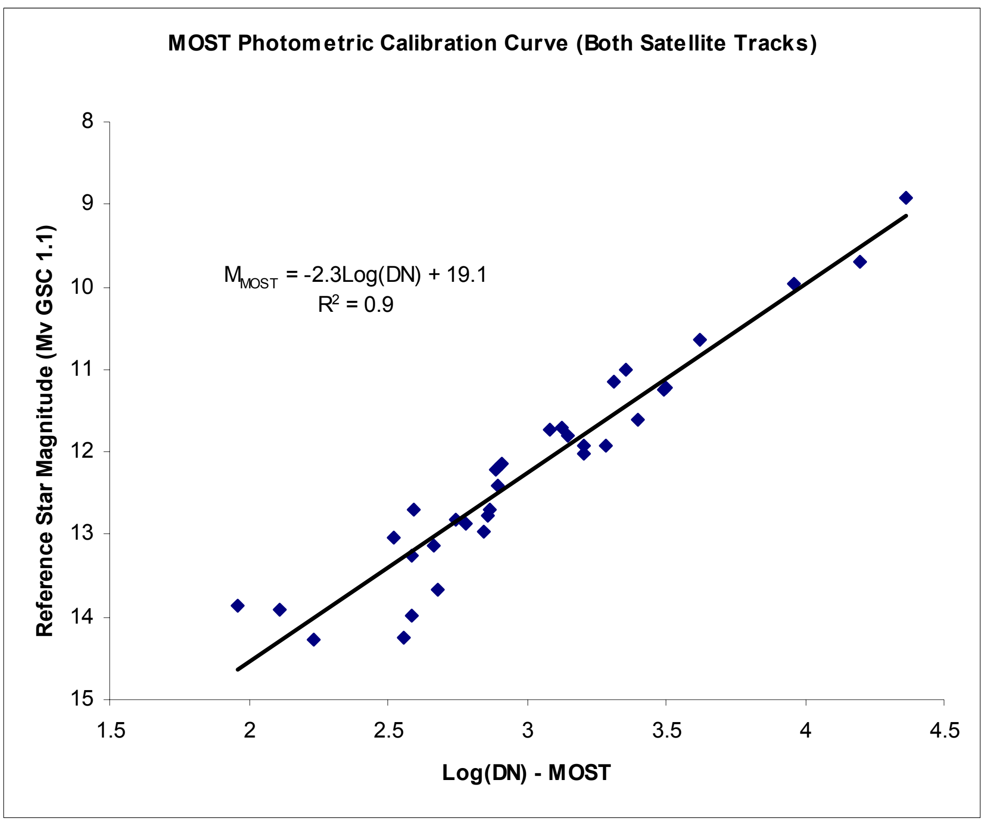


Figure 14. Photometric Calibration curve using the brightest stars in both images

[**] Maxim/DL is a software tool developed by Cyanogen Inc. and is targeted at advanced amateur astronomers.

7.2 Photometry Estimates

A rectangular measurement region was taken around each satellite streak to determine signal+sky counts. A separate sky count region was also determined. The difference between these regions determines the intensity of the satellite streak. Four measures were taken and averaged to reduce the impact of CCD pixel to pixel variation for each image. A summary of the results follows in table 5.

Table 5. *MOST Photometry of Satellite Streaks and Background Data*

QUANTITY	1ST TRACK (28190)	2ND TRACK (26360)	UNITS
M_{GPS} (apparent)	**12.1 ± 0.2**	**11.5 ± 0.1**	$M_{V\ MOST}$
M_{GPS} (normalized)*	11.7	11.2	$M_{V\ MOST}$
Phase Angle	21.0	17.1	Degrees
Streak S/N Ratio (aggregate)	4.9	12.3	ADU signal / ADU noise
Sky Brightness	18.3	17.9	$M_{V\ MOST}$ / arcsec^2

*The apparent satellite brightness is inverse-square normalized to 20,000 kilometres range.

Both satellites were nearly equivalent brightness at the times of observation despite the first satellite streak appearing ‘dimmer’ than the second satellite streak as discussed previously. This is due to the trailing loss effect as the integration time per pixel for 28190 is traveling over the field of view at 75 arcsec-s^{-1}, while the second satellite streak is moving considerably slower (33 arcsec-s^{-1}) allowing more light onto the CCD pixels during that time, boosting the SNR for the second track and making it appear brighter.

The sky brightness was calculated by taking the modal pixel count for each image and dividing by the square of the pixel scale (8.9 arcsec^2) to determine the counts per square arcsecond. Using the calibration rule given in figure 17 the background estimate was found to be 18.3 and 17.9 magnitudes per square arcsecond. This is relatively bright, and the exact source of the background illumination is not entirely clear but is likely due to the light leak or the stray light issue mentioned in Section 3.1.

7.3 Photometry Error Sources

There are several sources of error inherent in the approach used to estimate the satellite streak brightness. To begin, CCD calibration frames such as “dark” and “flat field” data were not available as MOST does not employ a mechanical shutter or have the ability to take ocean flats. Pixel to pixel sensitivity variations are therefore inherent in the photometry estimates.

A fundamental tenet of differential photometry assumes that the target object and reference stars have similar colors. This ensures that the relative intensities of target and reference

source are due to flux differences only. No extra effort was spent to validate the color of the background stars as this information is not always available. Block IIR GPS spacecraft are known to have color indexes of B-V =1.3 suggesting red (M-type) stars are a close match to the satellite's color. Given that the MOST instrument spectral response peaks near 600 nm this offers some reassurance that the photometry measurement is a decent approximation to the satellite's true magnitude. Variable star brightness was also ignored for the MOST magnitude calibration. No extra effort was spent determining the population of variable stars in the fields of view of MOST and is absorbed into the error estimate for these observations.

To perform differential photometry, reference magnitudes for the background stars are needed. The Hubble Guide Star Catalog was used despite known photometry errors of 0.3 magnitudes (1σ) with 10% of the catalog errors greater than 0.5 magnitudes [12]. For this test the GSC has sufficient accuracy as photometry was not the primary emphasis of the tracking experiments. A better technique would be involve use of a higher accuracy reference catalog (USNO-B [15] for instance) or by calibrating MOST with respect to Landolt [16] star fields and adding small color correction terms to better determine the curve of counts to magnitude.

The MOST satellite incorporates two side-by-side Marconi 47-20 CCDs. One CCD acts as a star-tracker; while the other is the Science instrument. Early in the MOST program, a cross-talk noise issue was encountered with the CCDs. The star tracker is read out 5 times per second in order to guide the satellite's ACS to arcsecond level precision. During star tracker read-out, electronic noise migrates onto the Science CCD. The result is that a small band of noise, nearly 3 times the background deviation is seen in the images; an example of the read noise is shown in figure 15. This noise was investigated thoroughly by the MOST science and contractor teams during spacecraft construction and the team was able to reduce this effect considerably through better grounding practices however some residual effects remain to this day. Care was taken to avoid the cross talk regions when measuring the satellite's magnitude.

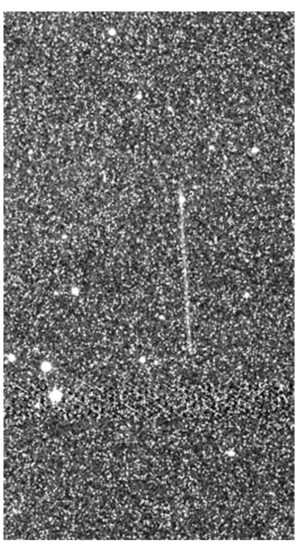


Figure 15. Photometry Error Sources

An interfering star is visible at the top of the satellite streak This tends to brighten the satellite streak.

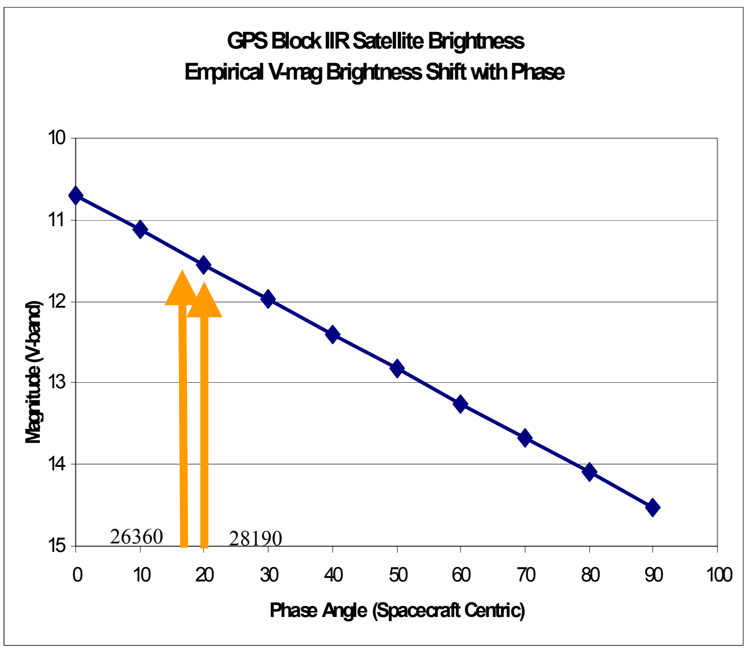
A banded region of cross-talk noise generated by the repeating downloads of the star tracker is visible below the satellite streak. The cross talk noise creates the salt and pepper appearance on the image. Normally the image background noise varies ~6-7 counts, in the cross talk region, the image noise varies by as much as 21 counts.

Stars also affect the quality of the measured satellite brightness as they are unintended sources of noise relative to the target streak. For instance, the satellite streak of 28190 contained a star along the streak segment (a star wart) near the streak endpoint. As a result, this unwanted star's flux is contained in the satellite brightness estimate, artificially brightening the satellite's track.

7.4 Comparison to Ground-Based Measurements

The MOST photometry was validated by comparing the results with ground based photometry measurements of GPS satellites.

Vrba [10] reported the magnitude-phase relationship for the Block IIR series of spacecraft to be -0.0425 magnitude degree^{-1}in V-band. For this cross-check, this would be an adequate approximation despite the red-sensitive nature of MOST's instrument. Vrba's measures show that Block IIR satellites have an intrinsic** V-band magnitude of 12.4. Using this information, one can plot the expected magnitude versus phase angle brightness change for Block IIR spacecraft (figure 16). MOST's normalized measurements of the GPS IIR satellite's brightness were 11.7 (φ=20°) and 11.2 (φ=17°), these measurements are consistent within 0.2 magnitudes of the empirical data provided by Vrba [17], giving confidence in the measured magnitudes and the process used to determine them.



	28190	26360
Measured Apparent Magnitude	12.1	11.5
Measured Magnitude (Normalized)	11.7	11.2
Empirical Theory	11.6	11.4
Residual	0.1	-0.2

Figure 16. GPS IIR empirical satellite brightness versus phase angle. Both measurements from MOST are consistent with the plot.

** Vrba defines standard, photometric conditions for a GPS satellite for be 140 degrees phase angle (observer-centric phase angle, not target-centric), normalized to 20,000 kilometers range and 1 AU distance from Sun to GPS.

8. MOST Telemetry

Requests from the SofSP and DRDC Ottawa were sent to the MOST satellite operator for segments of the MOST telemetry stream. In particular, there was interest in the CCD temperature stability and ACS pointing performance of the spacecraft during the two satellite acquisitions. The operator parsed the Whole Orbit Data (WOD) telemetry stream to extract the telemetry of interest.

8.1 MOST CCD Temperature Profile

The MOST instrument is passively cooled via a radiator located on the +X face of the spacecraft, (this is in the same direction as the science instrument boresight) which is pointed towards deep space. The radiator rejects heat to the cool celestial background, reducing the CCDs' operating temperature. Cooling CCDs minimizes thermal (dark current) noise, necessary for accurate photometry and imaging. During MOST's normal orbital operations, the Science CCD temperature is sampled at ~6 minute intervals. This provides the science and contractor teams with an indicator of the relative performance of the sensor.

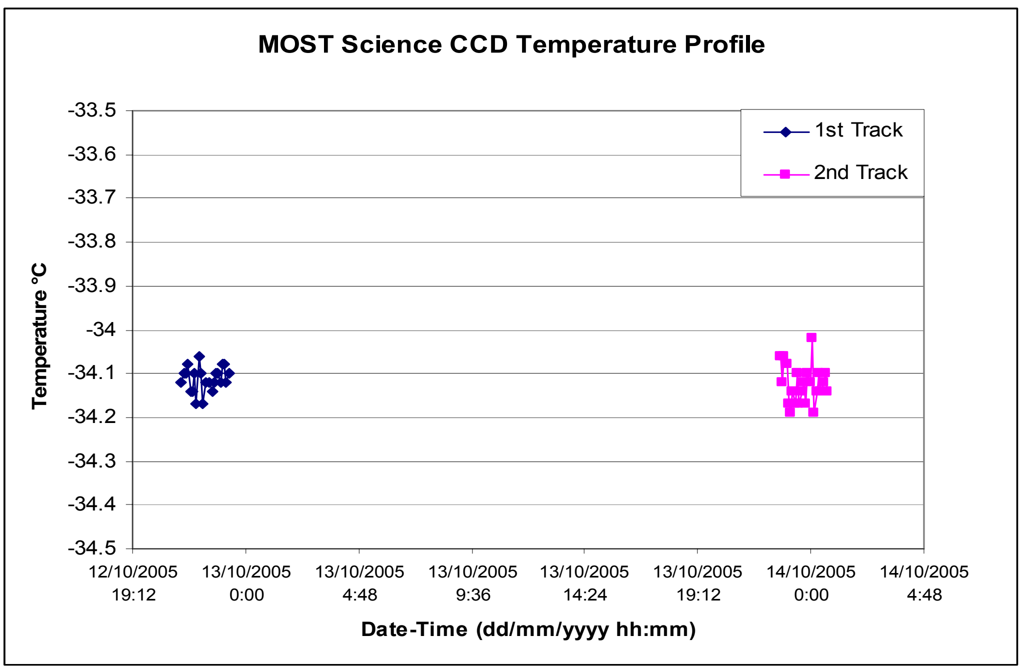


Figure 17. MOST Science CCD temperature profile. The operating temperature of the CCD was -34.1 °C with temperature stability (ripple) of 0.05 °C.

The operating temperature of the Science CCD was -34.1°C with a temperature ripple of ~0.05 degrees C (Figure 17). MOST's nominal operating temperature was expected to be -40°C [8] and was designed to maintain temperature stability within ±0.1°C. It is unknown if MOST achieves the desired -40 degree set point, but this test does show that MOST can

maintain temperature stability within the 0.1 degree limit. This helps manage background noise to a predictable level during imaging which will help in the detection of satellites and especially during long duration exposures of asteroids with NEOSSat.

8.2 MOST ACS Error

The MOST spacecraft uses Dynacon microwheels [7] to control spacecraft attitude with a fine pointing stability of ~3 arcseconds for exposure durations of 30 seconds. This is a very high performance ACS stability for a microsatellite.

WOD data from the ACS control system is normally available at 7-11 second intervals for Roll, Pitch and Yaw. The graphs in figures 21 and 22 show the ACS error between targeted and actual pointing attitude as measured by the startracker CCD. Roll error is generally larger than the pitch and yaw error as roll about the telescope boresight is difficult to measure precisely with a star tracking CCD. Yaw and Pitch correspond roughly with the J2000 Right Ascension and Declination directions for the observations in question. The satellite operator attempted to align the long axis of the Science CCD imaging field with the direction of motion of the satellite to increase the likelihood of capturing the satellite on the image.

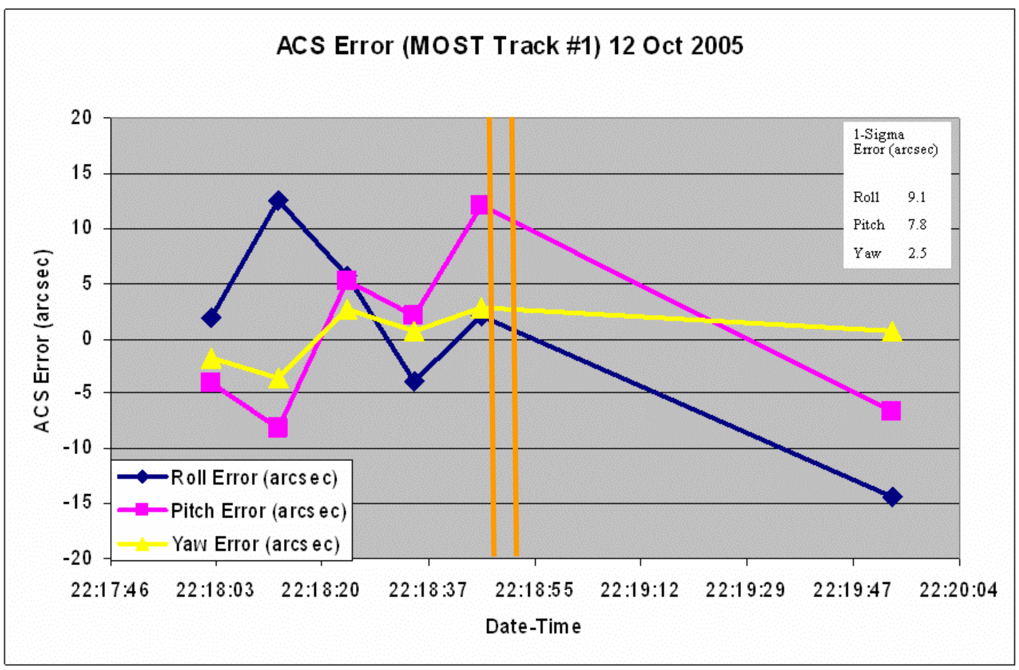


Figure 18. MOST ACS Error profile during the 1st satellite track on 28190.

The first satellite track shows 7.8 and 2.5 arcsecond error in pitch and yaw respectively. Both of these axes directly affect the spacecraft's ability to form an image on the CCD. In figure 18, the image start and stop exposure times are indicated by the orange vertical bars. It is seen that there are no WOD attitude error samples during the exposure of the image until a minute later. Assuming that the attitude drift error in pitch and yaw are consistent with the slopes shown between the two orange lines, one can estimate the amount of ACS error observed in

the image's formation. The astrometry of the image indicated that 8.6 arcsecond stellar FWHM was observed which is slightly higher than the 7 arcsecond design of the telescope. This suggests that ACS error may have had a slight effect on the formation of image stars by smearing through ACS jitter.

The second track shows very good pitch and yaw ACS behaviour. The resulting in 0.3 and 0.5 arcsecond ACS errors (figure 19) yielded FWHMs of 7 arcseconds, consistent with the telescope design and indicating that the spacecraft's ACS was performing better during the second image acquisition.

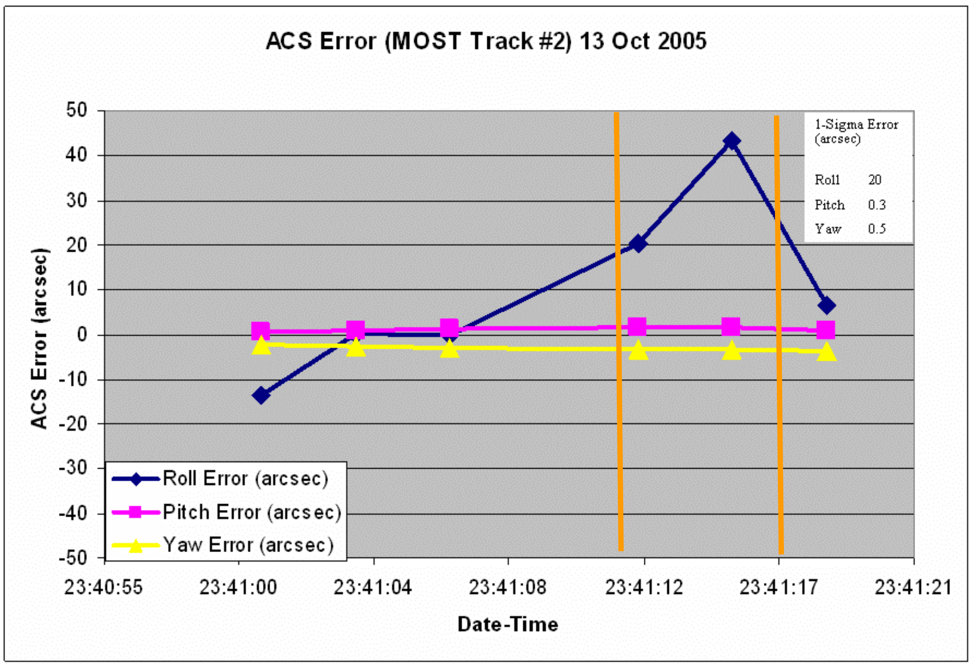


Figure 19. MOST ACS Error profile during the 2^nd satellite track on 26360.

While the first ACS results show that the spacecraft was not pointing as accurately as the second track, both show that a MOST-like ACS can take very good astrometric imagery. The next logical step is to test ACS agility where the microsatellite rapidly slews, achieves fine pointing lock, takes an image, breaks lock and slews to its next targeted attitude with a five minute cadence. This is a design driver for the NEOSSat mission and is a necessary capability to pursue a space-based space surveillance capability. This test is not feasible with MOST as it lacks the memory needed in order to take two sequential images, but some combination of subimages/rasters possibly could be arranged to test the agility aspect required by NEOSSat.

9. Conclusions

MOST has demonstrated the ability of a microsatellite to conduct deep space satellite tracking observations, observing two Block IIR GPS satellites with ranges of ~24,000 kilometres using star stare mode (SSM). The fact that satellite streaks were seen suggests that the planning process to point MOST towards its targets works.

The orbital metric error residuals were determined to be 13 arcseconds RMS. This is outside of the performance specifications for Sapphire and NEOSSat but is nonetheless very good for MOST considering the fact that MOST was not designed to perform imaging, let alone attempt satellite tracking observations. It is suspected that the major component of this error is due to unmodelled systematic timing effects inherent in the MOST instrument.

MOST detected and produced astrometric-quality streaks on GPS IIR-11 and GPS IIR-04. The targeted GPS satellites were favourably illuminated, and MOST measured their magnitudes to be $M_{MOST} \sim 12.1$ and 11.5. This is a MOST-specific magnitude and is V through R sensitive due to the spectral sensitivity of instrument on MOST. Comparable V-band measurements of Block IIR satellites from Earth's surface suggest that these photometric measurements are consistent within 0.2 magnitudes. The background sky was also measured and averaged 18.1 magnitudes-arcsec^{-2} during satellite tracking. This elevated background is suspected to be due to stray light from Earth's limb or possibly from a light leak making its way onto the detector plane of the MOST spacecraft.

This test has shown that the MOST instrument and ACS show technical promise for use in a space surveillance system. Future space surveillance testing with MOST, if possible, should involve either collection of more satellite tracks, or a test of the ACS agility of the spacecraft mimicking NEOSSat's intended mode of operation.

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Annexes

Annex A – Geometric Access Constraints

Several quantitative constraints have to be respected during space based satellite tracking. These are tabulated in the following table. These constraints were applied in STK when planning the observations. Some constraints, such as the CVZ constraint, are MOST specific and are not necessarily required for observing deep space satellites.

Access Constraints During MOST Observations

OBJECT	CONSTRAINT	LIMITS	UNITS/COMMENTS
MOST (Observer)	Line of Sight (LOS) to Dynacon*	True	
	MOST outside of SAA	True	
GPS (Target)	Fully illuminated (Direct Sun)	True	Target must not be in Earth's shadow
	Falls within CVZ	True	Target must fall within MOST's CVZ operating region
(Observer – Target) Access Constraints applied as basic constraints on MOST	Minimum angular rate (ω)	10	arcsec s^{-1}
	Maximum angular rate (ω)	100	arcsec s^{-1}
	Maximum phase angle (φ)	50	deg (CVZ dominant constraint)
	Lunar Exclusion Angle	25	deg
	Solar Exclusion (Elongation) Angle	Ignored, (CVZ is anti-sunward and is the dominant constraint)	deg
	Earth Limb Exclusion Angle	20	deg
	Number and quality of guide stars dictating roll (ψ) constraint†	3 stars minimum Mag 11 or brighter	Applied by spacecraft operator

These constraints need to be respected during each access.

*Dynacon now indicates that the first constraint is no longer necessary, as time-tagged imaging commands can now be executed anywhere on orbit.

†Dynacon applies another roll constraint on the attitude of the spacecraft to ensure that sufficient guide stars fall on the star-tracking CCD to achieve fine pointing lock. Since MOST is looking within the CVZ, sufficient sunlight on the negative X solar panel is available.

Annex B – Look Angle Product

MOST Satellite Imaging Attempts
October Engineering Testing / Star Transition
R.L. Scott Defence R&D Canada Ottawa
11 Oct 2005 3:05 EST
Coordinate Frame: J2000 spacecraft centric
****

**1st Access Interval 12 Oct 2005 22:16-22:21 UTC
Satellite-MOST-To-Satellite-USA_177 (28190) Epoch 2005-283.25
Average Angular Rate: 74.0 "/s
Phase Angle: 20.1 deg
Exposure Time: 5 Seconds

Time (UTCG)	Range (km)	Right Ascen (deg)	Declination (deg)
12 Oct 2005 22:18:30.000	23962.480544	19.30418	29.00297
12 Oct 2005 22:18:40.000	***23953.480226***	***19.24201***	***28.79664***
12 Oct 2005 22:18:50.000	23944.944597	19.17842	28.59113
12 Oct 2005 22:19:00.000	23936.873104	19.11341	28.38649
12 Oct 2005 22:19:10.000	23929.265086	19.04702	28.18272
12 Oct 2005 22:19:20.000	23922.119795	18.97925	27.97985
12 Oct 2005 22:19:30.000	23915.436398	18.91014	27.77790
12 Oct 2005 22:19:40.000	23909.213975	18.83969	27.57690
12 Oct 2005 22:19:50.000	23903.451520	18.76793	27.37686
12 Oct 2005 22:20:00.000	23898.147944	18.69488	27.17781
12 Oct 2005 22:20:10.000	23893.302072	18.62056	26.97977
12 Oct 2005 22:20:20.000	23888.912645	18.54499	26.78276
12 Oct 2005 22:20:30.000	23884.978320	18.46818	26.58680

**2nd Access Interval 13 Oct 2005 23:37-23:42 UTC
Satellite-MOST-To-Satellite-USA_150 (26360) Epoch 2005-283.43
Average Angular Rate: 33.5 "/s
Phase Angle: 17 deg
Exposure Time: 7 Seconds

Time (UTCG)	Range (km)	Right Ascen (deg)	Declination (deg)
13 Oct 2005 23:40:00.000	23195.566202	4.52957	17.80871
13 Oct 2005 23:40:10.000	23200.816880	4.49887	17.72062
13 Oct 2005 23:40:20.000	23206.334883	4.46666	17.63351
13 Oct 2005 23:40:30.000	23212.118978	4.43297	17.54740
13 Oct 2005 23:40:40.000	23218.167917	4.39779	17.46231
13 Oct 2005 23:40:50.000	23224.480432	4.36116	17.37825
13 Oct 2005 23:41:00.000	23231.055244	4.32307	17.29525
13 Oct 2005 23:41:10.000	***23237.891059***	***4.28356***	***17.21330***
13 Oct 2005 23:41:20.000	23244.986569	4.24263	17.13245
13 Oct 2005 23:41:30.000	23252.340452	4.20029	17.05269
13 Oct 2005 23:41:40.000	23259.951372	4.15657	16.97405
13 Oct 2005 23:41:50.000	23267.817983	4.11148	16.89655
13 Oct 2005 23:42:00.000	23275.938922	4.06504	16.82019

Annex C – Correction for Annual/Orbital Aberration

Taken from “High Precision Satellite Astrometry and Photometry” by Sydney[18]

α,δ – apparent right ascension and declination

α’,δ’ – corrected right ascension and declination

χ, β – Lorentz Scaling Parameters

$\mathbf{v'_{Earth}}$, $\mathbf{v'_{Observer}}$ – J2000 velocity of Earth and observer with respect to the Barycenter of the solar system

c = speed of light

$$r' = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos(\delta)\cos(\alpha) \\ \cos(\delta)\sin(\alpha) \\ \sin(\delta) \end{pmatrix}$$

$$v' = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \frac{v'_{Earth} + v'_{Observer}}{c}$$

$$\beta = \sqrt{1 - \left\| r' \bullet v' \right\|^2} \qquad \chi = \frac{r' \bullet v'}{1 + \beta}$$

$$r_{corr}' = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \beta x + v_x + \chi v_x \\ \beta y + v_y + \chi v_y \\ \beta z + v_z + \chi v_z \end{pmatrix}$$

$$\alpha' = \arctan\left(\frac{y'}{x'}\right) \qquad \delta' = \arctan\left(\frac{z'}{\sqrt{x'^2 + y'^2}}\right)$$

Annex D – Ephemeris Error During Tracking

A space-based space surveillance system requires an accurate orbital positioning capability for itself. An image of a distant satellite without an accurate position of the observer is of little value as parallax can severely limit the use of optical observations. For many celestial objects, parallax can be ignored, but for satellites orbiting the Earth, parallax must be taken into account. To do so, accurate orbit determination of the observing spacecraft must be performed.

MOST does not employ a GPS or coherent ranging transponder for orbit determination. In order to establish the position of MOST during the observations of GPS targets, the relevant two-line elements sets were obtained from the SSN. This provides an approximation of the orbital position of MOST but does not have the precision of dedicated orbit determination systems. Two line element sets are a set of 'mean elements' designed to be used with General Perturbation Theory and lack the accuracy to be used successfully within tens of meters [19] which is necessary for space-based satellite tracking. Kilometre-scale positioning errors were anticipated and DRDC was willing to tolerate more than ~10 arcseconds of ephemeris error during the MOST tracking attempts.

Fortunately, during both days which MOST tracked the GPS targets, the SSN updated MOST's elsets. Comparing epoch days 2005-285 and 2005-285 it is seen that the difference between the two elsets is less than 120 meters (figure 20). Follow-up elsets on 2005-286 agree to within 300 meters. This suggests that MOST's actual ephemeris error is much less than the kilometer scale errors anticipated prior to the tracking attempt. For both satellite tracks, this incurs an ephemeris error less than 1 arcsecond.

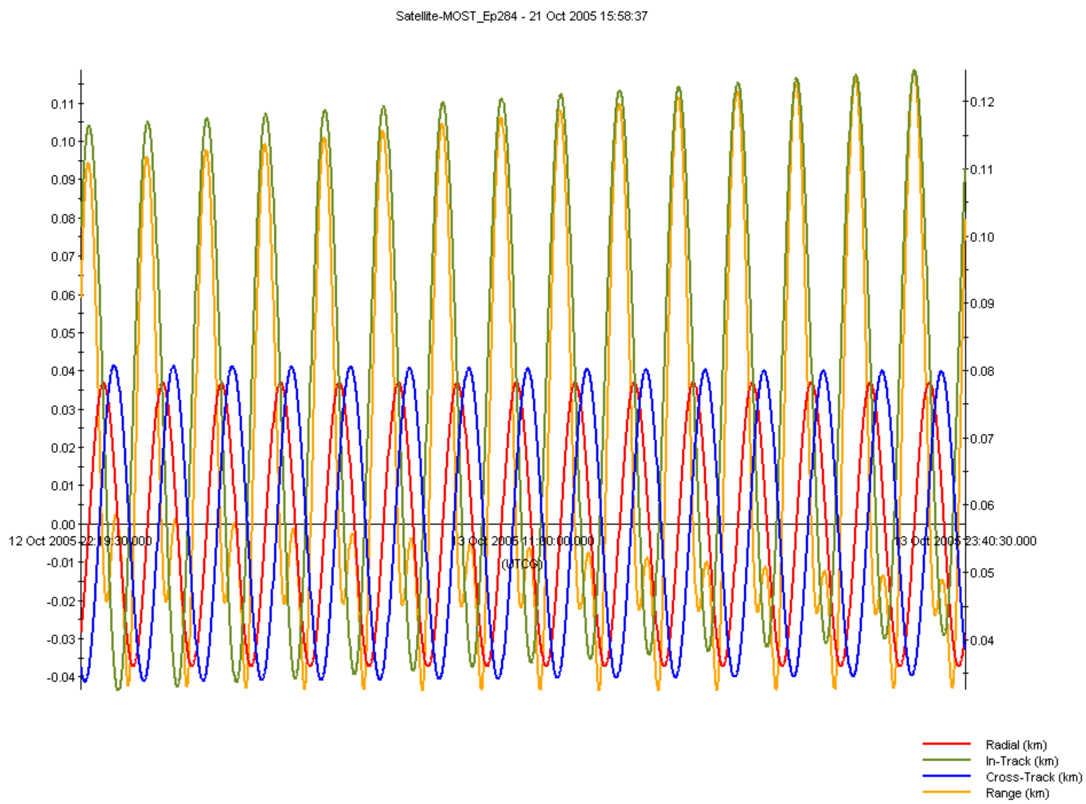

Figure 20. Radial-Intrack-Crosstrack (RIC) differences between MOST elsets of Epoch Dates: 2005-284 and 2005-285. The times of the satellite observations are at the start and finish of the figure. The differences between the two element sets suggest the ephemeris error was less than 120 meters during the tracks.

List of symbols/abbreviations/acronyms/initialisms

ACS	Attitude Control System
ADU	Analog to Digital Unit
AOS	Acquisition of Signal
CCD	Charged Coupled Device
CF	Canadian Forces
CIS	Commonwealth of Independent States
COTS	Commercial Off-The-Shelf
CSA	Canadian Space Agency
CVZ	Continuous Viewing Zone
DEC	Declination
DND	Department of National Defence
DRDC	Defence R&D Canada
FITS	Flexible Image Transport System
FWHM	Full Width Half Maximum
GPS	Global Positioning System
GSC	Guide Star Catalog
HEOSS	High Earth Orbit Space Surveillance
IOC	Initial Operating Capability
J2000	Celestial coordinate reference frame corresponding to the mean equator and equinox of Jan 1.5 2000.
kB	kilobyte
LAGEOS	Laser Geodynamics Satellite
LOS	Loss of Signal

MB	MegaByte
MOST	Microvariability Oscillation of STars
MSX	Midcourse Space Experiment (DoD research spacecraft)
NASA	National Aeronautics and Space Administration
NAVSTAR	NAVigation Satellite Timing and Ranging
NEA	Near Earth Asteroid
NEOSSat	Near Earth Orbit Surveillance SATellite
NESS	Asteroid detection mission of NEOSSAT
NGA	National Geospatial Intelligence Agency
NORAD	North American Aerospace Defence Command
RA	Right Ascension
RIC	Radial, Intrack, Crosstrack
RMS	Root Mean Square
RSO	Resident Space Object
RSSS	Russian Space Surveillance System
SAA	South Atlantic Anomaly
SAO	Smithsonian Astrophysical Observatory
Sapphire	A Canadian DND program to construct an operational space surveillance system
SBSS	Space Based Space Surveillance
SBV	Space Based Visible
SNR or S/N	Signal to Noise Ratio
SofSP	Surveillance of Space Project
SSN	Space Surveillance Network
STK	Satellite Tool Kit
STRATCOM	Strategic Air Command

TDP	Technology Demonstration Program
TDRS	Tracking and Data Relay Satellite (NASA)
TLE	Two line element set
UBC	University of British Columbia
USNO	U.S. Naval Observatory
UTIAS	University of Toronto Institute for Aerospace Studies
UTC	Universal Coordinated Time
WCS	World Coordinate System
WGS-84	World Geodetic System 1984
WOD	Whole Orbit Data (telemetry)

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On October 12th 2005, Canada's MOST spacecraft acquired Canada's first microsatellite-based observations of a deep space satellite. MOST repeated this success by conducting an observation on a different spacecraft the following day. This report summarizes the experimental setup, access particulars, metric and photometry data. Comparison of the derived orbital metric data with high precision ephemerides yielded root mean square errors of 13 arcseconds. The errors are shown to result largely from timing uncertainties inherent in the MOST spacecraft. The space-based photometric measurements of these spacecraft were consistent with ground based observations. Analysis of these results indicates that microsatellite platforms show technical promise as a low cost means to conduct space surveillance from an orbiting platform.

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